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Stylolites and sedimentary structures in the Cave-in-Rock fluorspar district, Southern Illinois

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STYLOLITES AND SEDIMENTARY STRUCTURES
IN THE CAVE-IN-ROCK FLUORSPAR DISTRICT
SOUTHERN ILLINOIS

BY

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A

THESIS

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ABSTRACT

This thesis deals with stylolites, slump structures, sulfides in the oolitic limestone, and geometry of the bedded fluorite deposits in the Cave-In-Rock fluorspar district, southern Illinois. Stratigraphic zones studied were: 1) the upper part of the lower Fredonia limestone member, 2) the upper part of the upper Fredonia limestone member, and 3) the upper part of the Renault formation.

Geometry of the ore rocks and related structures was investigated. Most of the ore is layered and constitutes part of the sedimentary strata.

Slump structures were observed and studied in detail. Most of the slump structures show evidence which indicates a sedimentary origin.

An extensive review was made of previous investigations of stylolites. Particular attention was given to the genetic criteria.

Megascopically, the stylolites are classified into the six basic patterns. Relationships of stylolites to individual rock grains are defined and classified. Aggregate stylolites were defined as those which have amplitude larger than the rock grain diameters; intergranular stylolites have an amplitude less than the grain diameter.

Detailed megascopic observations on the stylolites and related sedimentary structures and extensive microscopic study suggest that the stylolites were formed during compaction of semi-plastic sediments.

Detailed microscopic observations of the sulfide-wall rock relationships in the lower Fredonia limestone indicate a sedimentary origin of the sulfide.

ACKNOWLEDGEMENT

I wish to express my deep appreciation to Professor G. C. Amstutz, advisor of the writer's graduate studies, who offered many valuable suggestions and continuous interest during this thesis work. Dr. Amstutz also provided the writer with valuable literature related to the problems of this thesis.

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CHAPTER I. INTRODUCTION

The Illinois-Kentucky fluorite district is considered to be the largest known fluorite district in the world. The bulk of the ore mined at present comes from the Cave-In-Rock area, which is located in southern Illinois and covers an area of about 30 square kilometers.

The original work of this thesis consists of:

1) The megascopic and microscopic study of stylolites.

2) The investigation of slump structures and other sedimentary structures.

3) The determination of ore mineral distribution in relation to the sedimentary structures.

4) The examination of sulfides in oolitic limestone.

Special emphasis was put on the geometry, composition, and genesis of stylolitic seams.

During a graduate field trip to the southern Illinois fluorspar district with Dr. G. C. AMSTUTZ in early June 1961, the present thesis area was visited. Arrangements were made at that time through Mr. A. E. BRECKE, then Chief Geologist of the Ozark-Mahoning Company in Rosiclare, Illinois, to undertake the investigation. The time from 15 June to 10 September of 1961 was spent in the field. Most of the field work was done in the Hill, Oxford, and Deardorff mines in the Cave-In-Rock district. Field work included making detailed observations, drawings, and taking photographs. Samples showing critical relations were collected for study in thin section.

Observations with regard to sedimentary structures and stylolites were made also on the Arkansas novaculite in western Arkansas, and the

Jefferson City formation 7 km southeast of Rolla, Missouri.

About twenty publications have been written on the geology and mineral deposits of the southern Illinois fluorspar district. Most of the papers deal principally with fault structures. In some cases, slump structures and other features have been noted.

The literature appears to be lacking, however, in any detailed studies of geometry and wall rock ore-mineral relationships of slump structure, stylolites and sedimentary features.

More than one hundred twenty articles on stylolitic seams have discussed this topic in various publications. The origin of stylolite formation as discussed in the literature is still controversial. Little or no information is available on the possible diagenetic origin of stylolites.

During the fall and spring semester (1961-1962) and in part also during the summer of 1961, the samples and the information collected were studied. Laboratory work consisted of thin section, polished section, and insoluble residue studies, on both stylolites and ore minerals.

CHAPTER II. LOCATION AND ACCESSIBILITY

The area is located in the northeastern part of Hardin County near the southern extremity of the State of Illinois. The bedded deposits in the Cave-In-Rock fluorspar area occur in the northeastern part of the Illinois-Kentucky fluorspar district.

The name and location of the mines studied all occur in the Swanee Mine Quadrangle and are as follows: Hill mine, E. $\frac{1}{2}$ of Sec. 23, T. 11 S., R. 9 E.; Oxford mine, N. E. $\frac{1}{4}$ of Sec. 25, T. 11 S., R. 9 E.; Deardorff mine, N. $\frac{1}{2}$ of Sec. 34, T. 11 S., R. 9 E. (Figure 2).

Illinois State Highways 149 and 1 reach the area and pass through the towns of Cave-In-Rock, Elizabethtown and Rosiclare. The area may be reached via the Illinois Central Railroad which has a branch line that terminates at Rosiclare.

CHAPTER III. REGIONAL GEOLOGY AND TECTONICS

Geotectonically the Illinois-Kentucky fluorspar district lies on the extreme southern portion of the Illinois basin, surrounded by relatively high structural provinces, the Ozark Dome to the west, the Nashville Dome to the southeast, and far more to the northeast, the Cincinnati Arch.

Figure 1 is the geologic map of the district, as published by WELLER and GROGAN (1950). The geology of the Cave-In-Rock district can best be described as an area of relatively undisturbed sediments, except for the numerous faults.

The strata strike approximately N. 70° W. and dip homoclinally to the northeast (Figure 2). The average dip ranges from 3° to 5°. The oldest formation exposed in the Cave-In-Rock district, here defined as including all of Hardin County east of the Peters Creek fault, is the Fredonia limestone of the Mississippian System. The youngest formation which outcrops in the northern portion of the district is the Caseyville sandstone and conglomerate of Pennsylvanian age.

Quite close to the Cave-In-Rock district, about 18 km (10 miles) west of the mines studied, the Helderberg limestone of lower Devonian age is exposed at the central core (high) of the Hicks Dome which is an oval swell or uplift of strata and has its center in Sec. 30, T. 11 S., R. 8 E. From the center of the dome the rocks dip outward in all directions through a circular belt.

A large number of normal faults are associated with the broad domal structure. These faults have vertical displacements up to 500 m. The

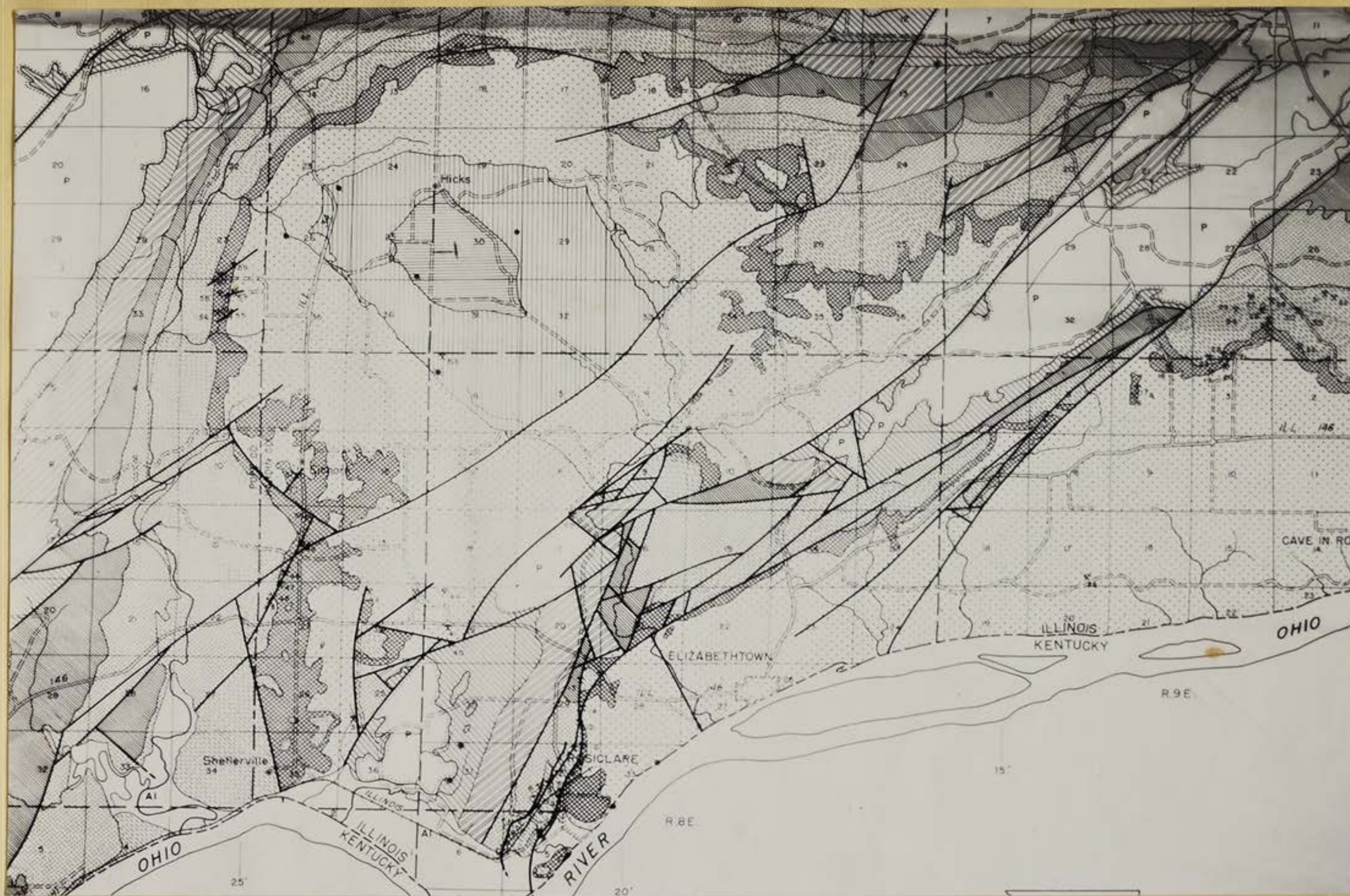
Peters Creek Fault is one of the major faults of the area and its hanging wall has been dropped down 300 m. in the area studied. The most frequent strike of the faults is N. 50° - 60° E.; however, faults striking from N. 25° to N. 70° W. occur in some of the mines in the district.

The most extensive example of the faults in the mines studied, having a displacement of up to about 4 m occurs in the Deardorff mine. The faults dip towards a basin of an asymmetric syncline along its flank which extends from the northeast end of the Deardorff mine. Displacements are relatively small and dips of the rock formations of as much as 30° in S. 10° W. direction can be measured.

An additional feature of interest occurring at the northeast end of the Deardorff mine is a dike, 25 cm in thickness dipping 65° to the northeast. The dike rock consists of microcrystalline carbonate with mosaic texture, intergranular cryptocrystalline silica and round bituminous material. It also contains round masses of fluorite. The bituminous material frequently serves as stylolitic seam material. The petrographical nomenclature of this dike rock is ambiguous. The first dike was recognized in the Crystal mine by NAKOWSKI (1949) who did not consider its possible origin. A similar dike is also known in the shaft #16 mine of the Ozark-Mahoning Company (BRECKE, personal communication). The origin of these dikes is questionable. The petrographic study of the present thesis, which established the presence of stylolites in the dike material suggests that the dikes are likely to be sedimentary.

The Oxford mine also contains faults. A normal fault near the shaft strikes N. 50° W., has a displacement of about 2 m, and contains angular breccias of dolomite of the Renault formation and fluorite. A few fractures with strike about N. 50° W. are also observed. The Hill mine is developed along the synclinal basins. Collapsed, brecciated and small synclinal structures are numerous in the Hill mine which will be discussed later.

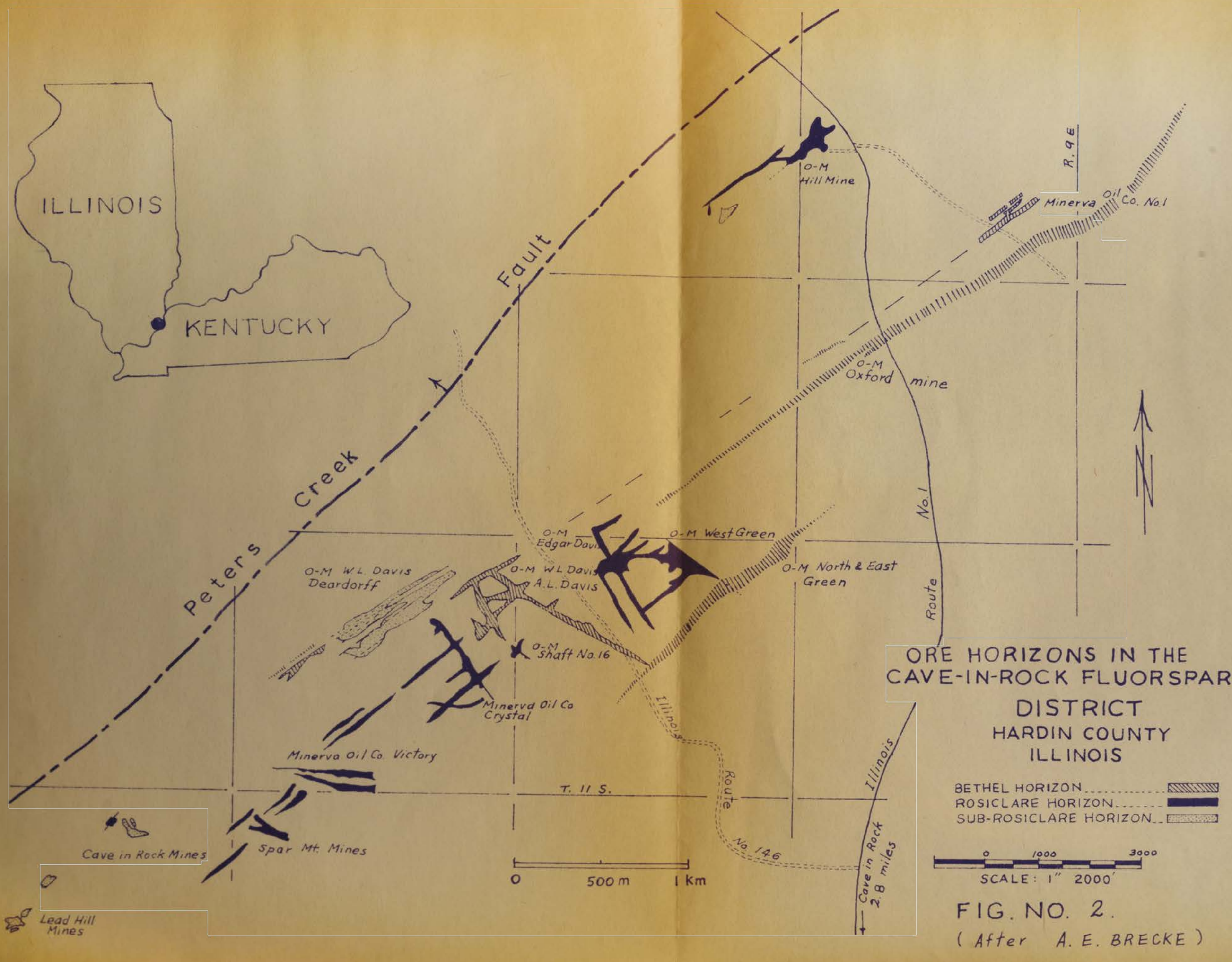
Dikes of igneous rocks in the district are reported by CURRIER (in WELLER, 1920). They are of three types: 1) lamprophyres, 2) mica-peridotites, and 3) volcanic breccia.



Key

- Al — Alluvium
- Cretaceous and Tertiary sands & gravels
- P — Pennsylvanian sandstone, conglomerate & shale
- Kinkaid limestone, Degonia sandstone, Clore limestone
- Palestine sandstone, Waltersburg sandst., Vienna limestone
- Tar Spring sandstone, Glen Dean limestone
- Faults
- Peridotite dyke underground
- Hardinsburg sandstone, Golconda limestone and shale
- Cypress sandstone, Paint Creek shaly sandstone, Bethel sandstone
- Renault limestone & shale, Levias limestone, Rosiclare sandstone
- Fredonia limestone, St.Louis limestone
- Warsaw limestone & shale, Osage limestone and chert
- New Albany shale & Devonian limestone
- Peridotite dyke or sill in outcrop
- "Explosion" breccia

Fig. 1. Geologic map of the fluorspar district of Southern Illinois. After WELLER, J. M. and R. M. GROGAN (1950).



ORE HORIZONS IN THE CAVE-IN-ROCK FLUORSPAR DISTRICT
HARDIN COUNTY
ILLINOIS

FIG. NO. 2.
(After A. E. BRECKE)

CHAPTER IV. STRATIGRAPHY

A. General

A condensed stratigraphic section of the formations which outcrop in the district is given below (thicknesses indicated are after BRECKE, personal information):

Pennsylvanian System		Caseyville Sandstone and Conglomerate	
Mississippian System	Chester Series	Golconda and Cypress formations	Alternating Sandstones, Limestones and Shales 250 m ±
		Bethel Sandstone 25 m	
		Renault formation	Renault Limestone 7 m +
			Sheterville Limestone and Shale 15 m
	Meramec Series	Ste. Genevieve formation	Levias Limestone 7 m
			Rosiclare Sandstone 10 m
			Fredonia Limestone 70 m -
		St. Louis Limestone 130 m	

1. Meramec Series

a. St. Louis formation

The St. Louis formation is well exposed along the Ohio River bluffs, from Elizabethtown to Cave-In-Rock and extends northward from the river bank for a distance of about 3 km. Farther to the north, the formation continues beneath the Ste. Genevieve limestone. Where exposed, it is blue to grey but where fresh it is dark blue to black. Much of the limestone of the formation contains considerable amounts of lenticular or irregular masses of chert nodules parallel to the bedding planes.

b. Ste. Genevieve formation

The Ste. Genevieve formation has been divided into three successive major members and one minor member which from the oldest to the youngest are: The Fredonia limestone, the Rosiclare sandstone, and the Levias limestone. The Fredonia limestone is further sub-divided into two. In the upper part of the Fredonia limestone there is a sandy zone which is called the "Sub-Rosiclare sandstone". TIPPIE (1945) proposed the name of "Spar Mountain sandstone" to replace the name "Sub-Rosiclare sandstone".

Fredonia limestone member: This member is divided into two parts, the "lower" and the "upper" which are separated by the Sub-Rosiclare sandstone. The characteristics of both sub-divisions range from dense lithographic to highly fossiliferous, oolitic limestone. Locally it is cross-bedded (Figure 5) and includes geodes (Figure 6). The top of the upper Fredonia limestone is defined to be below the greenish shale of the base of the Rosiclare sandstone.

Rosiclare sandstone member: This member is predominantly a fine grained and light grey to greenish calcareous sandstone. The basal portion contains locally a dark green to grey shale, up to a few meters in thickness in the

Hill mine. According to TIPPIE (1945), some of the basal sandstone contains as much as 75% calcium carbonate. The contact between the Rosiclare sandstone and the underlying Fredonia limestone is known to be locally disconformable (TIPPIE, 1945).

Levias limestone member: This youngest member of the Ste. Genevieve formation is variable in thickness ranging from 6 to 30 m thick in the district. It is grey to bluish, and varies from oolitic through fine grained to dense. The name Levias was proposed by SUTTON and WELLER (1932) to replace WELLER's (1920, p. 109) "Lower O'Hara".

2. Chester Series

a. Renault formation

Shetlerville member: This member is an interbedded shale and dark brown, fossiliferous, oolitic limestone.

Downey's Buff or Renault limestone member: The upper member of the Renault formation is the so-called "Renault-limestone" or Downey's Buff. It is a light brownish to greyish, oolitic, crystalline limestone. An oolitic chert bed occurs at the top of this member in the Oxford mine. It is overlain disconformably by the Bethel sandstone (WELLER, 1920, and TIPPIE, 1945). TIPPIE (1945) subdivided the member into five zones on the basis of insoluble residues as follows: Zones A, B, C, D, and E from the base to the top; zones D and E are locally absent.

b. Bethel Sandstone formation

This formation is a compact, medium grained, buff, grey and white sandstone which is quite permeable. In the Oxford mine the basal sandstone of the formation is cross-bedded, ripple marked, and argillaceous. A basal conglomerate has been noted from the other areas (WELLER, 1920).

c. Cypress Sandstone formation

The thickness of the Cypress sandstone is more than 35 m in Hardin County (WELLER, 1920, p. 177). It is similar to the Bethel sandstone in character.

Golconda formation

The Golconda formation is 50 - 60m thick in the vicinity of Minerva mine (NAKOWSKI, 1949, p. 20). It is essentially a succession of limestone and shales. According to WELLER (1920) the thickness is in excess of 35 m in the district.

B. Ore bearing horizons

The detailed stratigraphy is considered essential because of the obvious importance of "stratigraphic control" of these bedded ore deposits.

The bedded ores occur from a few meters below the Sub-Rosiclare contact to the Bethel-Renault contact. Figure 3 is a typical log of this stratigraphic section.

The most important three horizons of the ore are below the contacts of the lower Fredonia limestone with the Sub-Rosiclare sandstone, the Fredonia limestone with the Rosiclare sandstone, and the Renault limestone with the Bethel sandstone. The mines studied include all of these horizons. However, some minor ore bands occur in other horizons such as the Levias limestone and within the Fredonia limestone between the base of the Rosiclare sandstone and the top of the Sub-Rosiclare sandstone. Figure 4 shows the lithologic conditions of the three major contact zones below which ores occur. The main fluorite beds occur always in the top portions of the limestone units.

1. Sub-Rosiclare contact zone

The base of the Sub-Rosiclare sandstone, where it occurs, is usually about 20 m below the base of the Rosiclare sandstone. Figure 4C shows the lithologic variation of this zone in the Cave-In-Rock district. Figure 4-C-3 shows the zone in the southeastern part of the district where an average of 3 m of grey to green calcareous sandstone is present. The formation above the sandstone is the dark brown to oolite limestone and the underlying limestone is dense and light brown limestone. The northwestern limit of this condition is observed at the mine-walls of the southeast end of the Deardorff mine. Here the sandstone is stained with petroleum.

Figure 4-C-2 shows the lithology of the zone occurring northwest of 4-C-3. The condition shown on 4-C-1 is locally observed. The sandstone is totally absent in most parts of the Deardorff mine. In the area of the Sub-Rosiclare workings in the Hill mine, the thickness of the sandstone varies from zero to one meter.

In the Deardorff mine, a brownish to grey massive limestone and light brownish oolitic limestone below the contact zone decrease in thickness from approximately 1 m near the shaft to less than 20 cm within 200 m in the northwest direction.

These conditions of the zone suggest that the area northwest of the mine may have been subjected to subaqueous erosion which removed the sandstone and underlying limestone.

2. Rosiclare-Fredonia contact zone

The Rosiclare sandstone consists mainly of 7 - 9 m of grey to green, fine grained sandstone. The upper part of the formation is grey in color and is transitional upward through a sandy oolite into the Levias limestone. The lower part of the formation is usually green and may contain a shaly or silty zone.

The Fredonia limestone between the Rosiclare sandstone and the Sub-Rosiclare zone can be divided, on the basis of color, into three units.

The upper 3 m usually is light grey to buff oolitic limestone with minor amounts of dense limestone. The dense limestone may contain varying amounts of green shale. The oolitic limestone may or may not contain bitumen. Some variations of this section occur in the Hill mine where the dense limestone phases are more numerous and may be transitional into the greenish shale phase.

The top of the middle unit is usually marked by a thin shale. The limestone of this 6 m section is texturally similar to the upper unit but is of a definite brown color.

The third or lower unit of about 8 m consists of brown, dense to oolitic limestones.

The lithologic conditions of the Rosiclare-Fredonia contact zone have been observed in the Hill mine and the Oxford mine, and are shown on Figure 4-B.

3. Bethel-Renault contact zone

The Bethel sandstone is essentially a white medium grained quartz sandstone which contains minor amounts of shale as thin partings. The base of the formation at the contact with the underlying Renault limestone usually consists of about 1 m of cross-bedded and ripple-marked shaly sandstone. The ripple-marks are symmetrical and aqueous. The directions of the waves during the deposition of the basal shaly sandstone of 70 cm are measured at the shaft of the Oxford mine; they are, from the bottom to the top, as follows:

1.	E. W.	lower
2.	N. 80° E.	↓
3.	N. 70° E.	
4.	N. 45° W.	
5.	N. 30° W.	
6.	N. S.	upper

The Renault limestone in the district can generally be described as a light to brown crystalline limestone with an oolitic phase. The upper 5 m of the formation is relatively free of shale.

Throughout much of the district, the top of the Renault limestone contains 3 - 7 m of green calcareous shale under the Bethel sandstone. This shale has apparently been removed by means of subaqueous waves or currents near the Oxford mine.

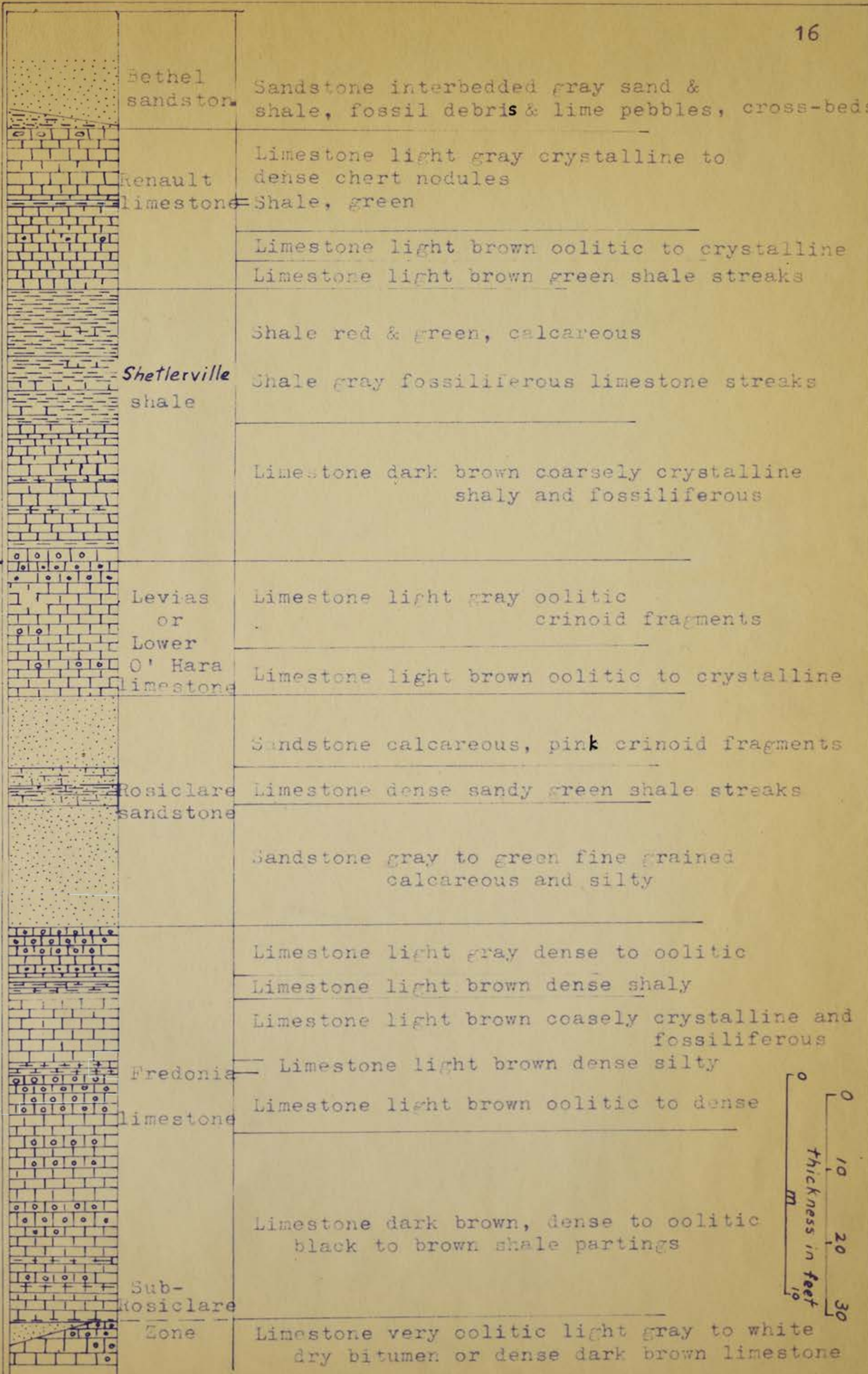
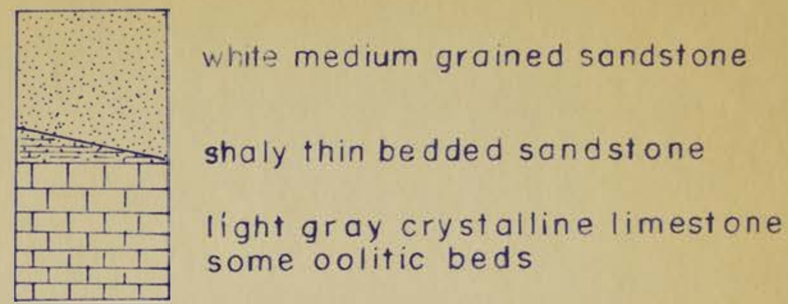


FIG. 3 . TYPE LOG ORE BEARING SECTION

After BRECKE (1961)



A. BETHEL-RENAULT CONTACT

B. ROSICLARE-FREDONIA CONTACT

C. SUB-ROSICLARE CONTACT

FIG. 4. DETAIL OF CONTACT LITHOLOGY
After BRECKE (1961)

Fig. 5. Cross-bedding of the Fredonia limestone. Picture is taken on State Highway 149, about 3 km east of Elizabethtown, Hardin County, Illinois.

Fig. 6. Geodes in outcrop of the Fredonia limestone. Picture is taken on State Highway 149, about 3 km east of Elizabethtown, Hardin County, Illinois.

CHAPTER V. MINERAL DEPOSITS

A. Introduction

The Illinois-Kentucky fluorspar district is the largest area of fluorite production in the world. Within the Illinois-Kentucky district, most of the production comes from the Cave-In-Rock bedded fluorspar district.

Here, neglecting the Kentucky area, the mineral deposits in the southern Illinois district can be classified according to the occurrence and the mode of deposition into three types: Vein deposits, bedded deposits, and residual deposits.

The area of the vein deposits in the so-called Rosiclare district is located in the southwestern part of Hardin County, Illinois. The fluorspar bearing veins of the Rosiclare district occur along the faults, following the Mississippian and, to a much lesser extent, the Pennsylvanian wall rocks. The thickness of the vein varies from a mere film to more than 10 m. The principal gangue mineral is calcite; other minerals in small amounts are quartz, sphalerite, galena, pyrite, chalcopyrite and barite (WELLER, GROGAN and TIPPIE, 1952, p. 99).

The area of the bedded deposits studied, the so-called Cave-In-Rock district, is located in the northeastern part of Hardin County, Illinois. The three major ore bearing horizons are: The Sub-Rosiclare zone, the Rosiclare-Fredonia contact zone, and the Bethel-Renault contact zone.

The size of the ore beds is variable; rarely more than 3 km long, 10-300 m in width, and 1-10 m in thickness. Figure 2 shows the ore bearing horizons which have been mined until August of 1961 in the Cave-In-Rock district. The principal ore minerals are fluorite, sphalerite, and galena.

In the Cave-In-Rock district, the bedded deposits show a closer relation to the sedimentary structures than to the faults.

Residual deposits have been mined at a few places along the outcrops.

B. Abundance and geochemistry of fluorine

Much has been published on the geochemistry of fluorine. Good summaries were given by RANKAMA and SAHAMA in 1950. Most of the information given below is taken from this summary.

Abundance of fluorine in the crust: CLARK (1920, p. 33) estimates the amount of fluorine in igneous rocks to be 0.091 per cent on the average. CLARK and WASHINGTON (1924, p. 40) calculated the abundance of fluorine in the earth's crust to be 0.03 per cent. GOLDSCHMIDT (1954, p. 569) states that this value should be increased at least to 0.08 per cent. Fluorine, the 13th element in abundance, is contained in the crustal rocks in the amount of 700 gm/ton (MASON, 1960, p. 44).

Fluorine in igneous rocks: The abundance of fluorine in several igneous rock types, in exhalations, and in sublimates of volcanic activity has been estimated by various investigators. Considerable quantities of fluorine are added directly to the orogenic cycle by volcanic processes.

According to CLARK (1924, p. 262), GAUTIER (1913) found 0.11 ppm of fluorine in volcanic gases from Vesuvius. ZIES (1938) calculated the quantity of HF evolved from the Valley of Ten Thousand Smokes in Alaska in 1919 as 200,000 tons and at least three quarters of these amounts were added to the sea. TAGEEVA (1942, re. RANKAMA and SAHAMA, 1950, p. 764) found 10.4 gm/ton fluorine in natural waters connected with volcanic activity. SHEPHERD (1940) found that some obsidian contained 0.07 per cent fluorine. BARTH (1947), on the basis of analyses of basalt collected from hot springs in Iceland, concluded that part of the fluorine of primary magmatic emanations reached the surface in the acid hot spring water, whereas the alkaline hot spring water lost all primary fluorine before it reached the surface.

GOLDSCHMIDT (loc. cit.) states that KORITNIG (1951) gave a value of 0.070 per cent fluorine for eruptive rocks.

The equal charge and the almost equal ionic size of the F^- (1.36 Å) and the OH^- (1.40 Å) explains the common occurrence of fluorine in silicate minerals containing OH^- groups in their structure. Fluorine is contained in micas, amphiboles, tourmaline, etc., which are the later minerals crystallized in the "reaction series".

Fluorine in sedimentary rocks: The fluorine content of the sedimentary rock is as variable as that of the igneous rocks. Generally it is greater in shale than in other sediments.

SHEPHERD (1935) found 1.100 gm/ton fluorine in a bottom mud from the Pacific Ocean. BARTH and BRUNN (1945, re. RANKAMA and SAHAMA, 1950, p. 764) found the following average values: 250 gm/ton fluorine in Ordovician limestones and 510 gm/ton fluorine in Ordovician and Cambrian shales. CROSSLEY (1944) found that the fluorine content in some coals was 0.080 per cent. HATCH (1938, p. 114) states that fluorite occurs as the cementing material of a Triassic sandstone, some of the rock containing as much as 26 per cent of this cement.

Fluorine in soil: The fluorine content is higher in soils of phosphatic composition than in other soils. The clay soils contain more fluorite than the other sandy soils (NAKOWSKI, 1952, p. 36).

According to RANKAMA and SAHAMA (1950, p. 764), fluorine is strongly absorbed by the bentonitic soil (up to 7,400 gm/ton fluorine in the bentonite).

Fluorine in water: NAKOWSKI (1952) determined fluorine content in fresh water from the Illinois-Kentucky fluorspar district varying up to about 0.0008 per cent. CLARK (1924, p. 122) states that fluorine content of the Atlantic Ocean determined by CARTON was 0.822 $mg/_l$, but GAUTIER's value was 0.3 $mg/_l$.

Some geochemical aspects of fluorite: RANKAMA (1954, p. 129) states that "the intensity of the thermoluminescence of fluorite appears to be a function of the age of mineralization of the deposit and is proportional to the total alpha-particle radiation received by the fluorite structure from the radioactive impurities contained therein."

TITLEY and DAMON (1961) report from the study of the ultraviolet absorption spectra of fluorite that "the 3050 Å defect density, per unit radiation dosage, appears to be a direct function of the age of fluorites."

POUS, MIGUEL and ALTABA (1962) conclude that the color of fluorite does not depend on the elements such as Ca, Mg, Al, V, Si, Fe, and Cu.

Many more reports have been published on fluorite and an adequate coverage of the literature would require very many pages. Since fluorite is translucent or transparent and also quite abundant, its zoning and inclusions have attracted many mineralogists and crystallographers. A summary of the inclusions and the problems related to them were published by STEGMULLER in 1952. In the same year, GROGAN and SHRODE wrote a paper on "formation temperatures of southern Illinois bedded fluorite as determined from fluid inclusions." That their method includes some untenable assumptions was demonstrated by CORRENS (1953). In a more recent paper FREAS (1961) again postulates validity for this method and uses it as over-all proof for ore genesis.

C. Fluorine minerals and fluorine cycle

The majority of the fluorine-containing minerals and their chemical compositions are included in the following list copied and augmented from EINECKE (1956, p. 8-9.). They are grouped according to their commercial significance.

1. Fluorine-containing minerals which are mined for commercial purposes.

Fluorite $CaF2$

Cryolite Na_3AlF_6

Chiolite $5NaF \cdot 3AlF_3$

2. In larger scale mineral deposits, but with lower fluorine content; commercially used minerals.

Fluorapatite $Ca_5F(PO_4)_3$

Lepidolite $Al_2O_3 \cdot 3\ SiO_2 \cdot 2(K,Li)F$

Zinnwaldite $F_2(KLi)_2FeAl_3SiO_5O_{16}$

Pyrochlore $NaCaCb_2O_6F$

3. Rare fluorine minerals.

Tysonite $(La,\ Ce,\ Di)\ F_3$

Sellaite MgF_2

Bastnaesite $(CeLa)_2F_6 \cdot (CeLa)_2O_3 \cdot 3CO_2$

Amblygonite $LiAl\ (F,\ OH)PO_4$

Topaz $Al_2SiO_4(F,OH)_2$

Parisite $CaF_2 \cdot Ce_2O_3 \cdot 3CO_2$

Fluocerite $(Ce,La,Di)_2OF_4$

Fluellite $Al(F,OH)_2 \cdot H_2O$

Phlogopite $FK_2Mg_3AlSiO_3O$

Prosopite $Ca(F,OH)_2 \cdot Al_2(F,OH)_6$

Pachnolite $NaF,\ CaF_2,\ AlF_3,\ H_2O$

Thomsenolite $NaCa(AlF_6) \cdot H_2O$

Yttrocerite $(Y\ Er\ Ce)F_3 \cdot 5CaF_2 \cdot H_2O$

Sulfohalite $NaCl — NaF \cdot 2Na_2SO_4$

Hieratite KF_2SiF_4

Kryptohalite $2NH_4F \cdot 2SiF_4$

Ferrucite $NaBF_4$

Avogadrite $(KCs)BF_4$

Kryolithionite $Na_3Al_2Li_3F_{12}$

Malladrite Na_2SiF_6

Matlockite PbFCl

Yttrocalcite $2YF_3 \cdot CaF_2$

Yttrofluorite YF_3

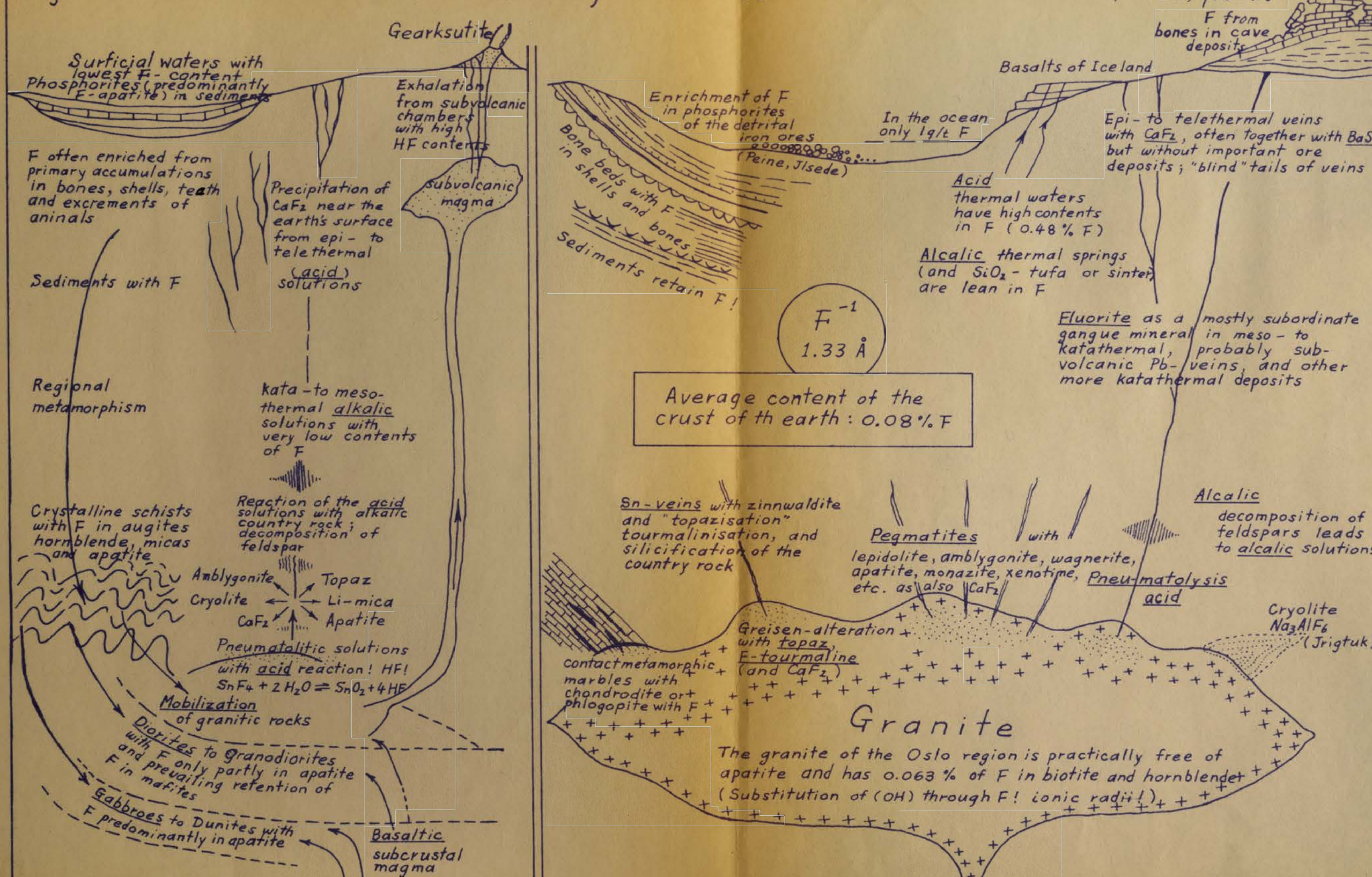
Neocerine $2MgO \cdot MgF \cdot CaF_2$

Belyankite $Ca_3Mg_3(FOH)_{13} \cdot H_2O$

Gearksutite $CaAl(FOH)_5 \cdot H_2O$

Figure 7 is a drawing of the possible occurrence and cycle of fluorine in the earth's crust (BORCHERT, 1953, p. 37).

Fig. 7. Geochemical occurrence and cycle of fluorine (after BORCHERT, 1953, p.37).



D. Fluorite deposits of the world

1. Occurrences

Fluorite has a wide distribution throughout the world. Deposits occur on every continent, and almost all industrialized nations have ready access to it. Some countries, however, still import this mineral while fluorite is being wasted as a gangue mineral from their mines.

EINECKE (1956) describes commercial deposits in the following nations or states:

<u>North America</u>

A. United States of America

1) Illinois-Kentucky
2) New Mexico
3) Colorado
4) Montana
5) Arizona
6) Texas
7) Utah
8) Idaho
9) Nevada
10) California

B. Canada

1) British Columbia
2) Ontario
3) Quebec
4) New Scotland
5) Newfoundland

C. Mexico

D. Greenland

<u>Middle and South America</u>

A. Mid-America

B. South America

1) Bolivia
2) Brazil
3) Argentina

Europe

A. Great Britain
B. Scandinavia
C. France
D. Germany
E. Belgium
F. Spain
G. Italy

Africa

A. North Africa

1) Tunisia
2) French Morocco

B. South Africa

1) Marico District
2) Zululand
3) North Transvaal
4) Okururu
5) Kalkfontein in southwest Africa
6) Wankie in Rodesia

Asia

1) U. S. S. R.
2) Turkey
3) India and Pakistan
4) China
5) Japan
6) Korea

Australia

1) Queensland
2) New South Wales
3) Victoria
4) Southern Australia
5) Western Australia

2. Production

World production in 1958 was estimated (Mineral Year Book, 1958, U. S. B. M.) at 1,760,000 tons, and this, divided percentage-wise by continents, is as follows: Europe, 37.8 per cent; North America, 35.6 per cent; Asia, 23.3 per cent; Africa, 2.7 per cent; and others, 0.6 per cent.

The production figures for the major producing countries for the same year in terms of short tons are:

United States	319,513	West Germany	129,966
Mexico	244,982	Spain	113,500
U. S. S. R.	180,000	France	99,000
China	165,000	East Germany	72,000
Italy	154,297	Canada	62,000

It is interesting to note that China was fourth in production. Other countries reporting some production, that is, under 10,000 tons, are Argentina, Japan, Sweden, Korea, South Rodesia, South-West Africa, and Australia. In other years small tonages have been indicated from Tunisia, Morocco, Norway, Bolivia, Brazil, India and Switzerland.

E. Geometric description of the Cave-In-Rock fluorspar deposits studied

1. General definitions and notes

For the purpose of this description, the term geometric is preferred over the term "structural geology" because it bears fewer connotations. What should be attempted in geological field work is, first of all, an objective description without any premature connotational expressions. The term structural geology has been used in the past fifty years in a rather interpretational way, at least in "economic geology". It almost always referred to anything cross-cutting as epigenetic, whereas we now know that faults are not the only "ore forming channels" and ore formation is not only epigenetic. Brecciation, too, may not necessarily be THE localizing feature in ore deposition, and neither is it always epigenetic. Intraformational brecciation is widespread.

It is necessary to separate the "observations" from the "interpretations" as meticulously as possible. The relationships between the "observations" and "interpretations" are illustrated in Figure 8.

Generally, geologic objects should be explored on both the macroscopic or large scale and the microscopic or small scale to approach a better understanding of the "how", "why", and "when". In this respect, the geometric classification of rock fabrics offered by AMSTUTZ (1959, p. 104) as modified for the AGI Data Sheet, is a useful first approximation. Figure 9 is a chart of this geometric classification.

An objective approach would generally include the following steps, going beyond a pure geometric description.

1. Fabrics (structural and textural)

    Size

    Form

Distribution

2. Compositional elements

Elements present (mineralogy and trace elements)

Relative abundance

3. Physico-chemical conditions (assumptions as to temperature and pressure)

4. Time (final interpretation)

It is safe to say that most of the banded ore deposits in the Cave-In-Rock district are, on a large scale, pattern 1 or stromatitic fabrics. However, numerous transitional fabrics such as pattern 3 and 10 were observed.

The small scale features, however, belong to various fabric patterns. For example, the breccia zone occurring at the northeast end of the Hill mine is merismitic or a network fabric, which is pattern 6 of Figure 9. The oolitic host rocks, on a microscopic scale, are ophthalmitic or disseminated fabric which corresponds to pattern 8.

In the forthcoming sections on the geometric features of the ore bands, these will be discussed step by step, and only to the point at which a preliminary interpretation could be offered with a fair degree of certainty.

It may be noted to begin with that much help was received from Mr. BRECKE and his manuscript, an abbreviated version of which is in print in Economic Geology. However, it will also be noted that the interpretations reached in this thesis often differ radically from those of Mr. BRECKE which, of course, does not discredit his keen observations and hard work.

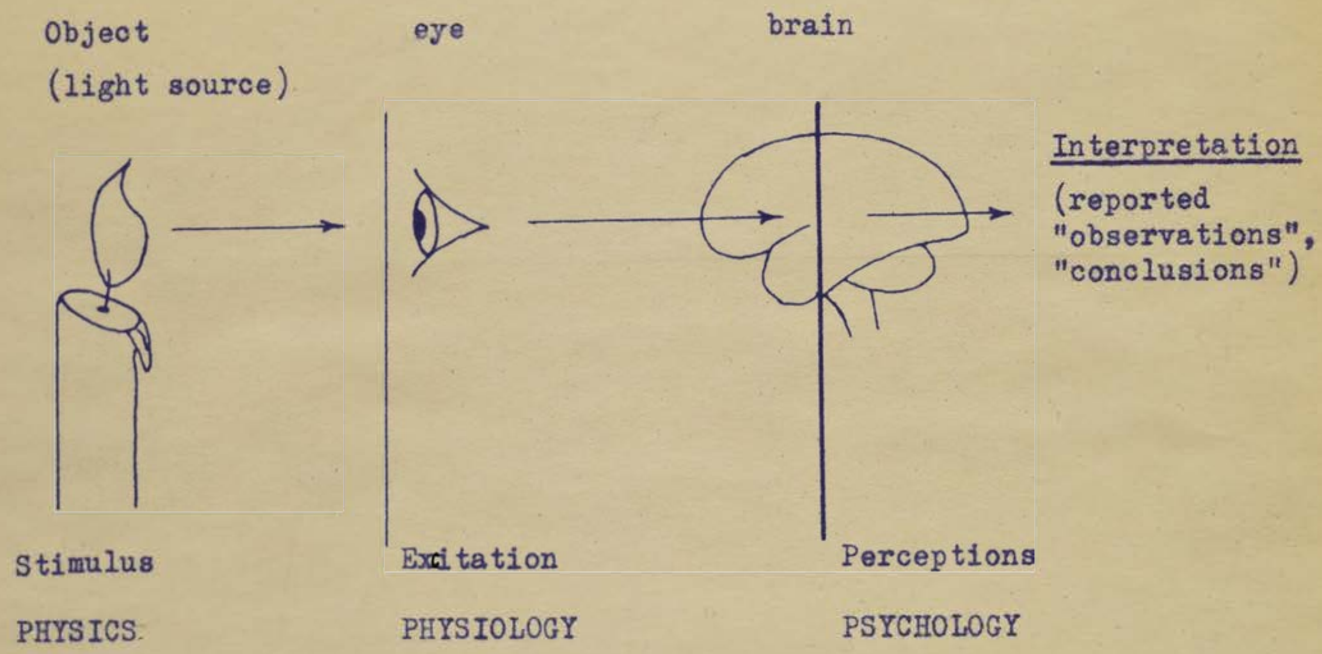
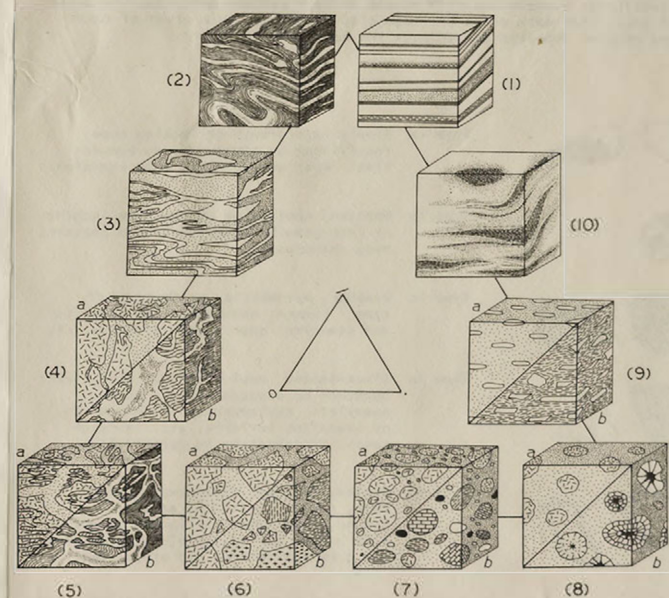


Fig. 8. Illustrations of the difference between an object and an "observation". Our observations of objects are not really "objective". They are"altered" or modified by physiological and psychological screens. Therefore they are really interpretations not only when past processes are involved which now can be studied only indirectly, but even to a certain extent and in a certain way when still objects or present day processes are viewed.

GEOMETRIC CLASSIFICATION OF ROCKS AND MINERAL DEPOSITS

AGI 21

by G.C. Amstutz
University of Missouri: School of Mines & Metallurgy



GEOMETRIC CLASSIFICATION OF ROCK FABRICS

free of genetic connotations

Pattern 1, 2, 3, and 10 = stromatitic or linear fabrics
Pattern 4, 5, and 6 = merismitic or network fabrics
Pattern 7, 8, and 9 = ophthalmitic or disseminated fabrics
Pattern 11 = massive or homogeneous fabric (to be placed at the fourth corner of a tetrahedron of which this drawing shows one face only).

(This purely geometric classification and nomenclature of rock fabrics is a systematic modification of patterns pictured by PAUL NIGGLI in "Rocks and Mineral Deposits," Basel 1948, San Francisco 1954, for chorismatic, polyschematic rocks and mineral deposits. Additional adjectives may be used in order to designate transitional patterns: pattern 3 may be called phlebitic stromatite, pattern 4a phlebitic merismite, pattern 8b miarolithic ophthalmite, and pattern 10 nebulitic stromatite.)

G. C. Amstutz, 1959.
(Proc.Geol.Assoc.Canada 11, p.104)

Additional copies of this data sheet may be obtained from the AMERICAN GEOLOGICAL INSTITUTE. Cost $0.10.

Fig. 9. Chart of the geometric classification of rocks and mineral deposits.

2. Hill mine

Ores are mined from two stratigraphic horizons, the Sub-Rosiclare-lower Fredonia and the upper Fredonia-Rosiclare contact zones. Structurally, this mine is developed along the synclinal and collapsed zones of the overlying basal sandstone beds of the Rosiclare sandstone.

Figure 10 shows contours on the base of the Rosiclare sandstone as constructed from drill hole data (after A. E. BRECKE) and elevations in the mine. The area northeast of the shaft shows the most intense collapse features.

The portion of this mine extending southwest from the shaft is more typical of most bedded deposits. Some areas show intense slump structures which will be discussed under the section on slump structures.

Figure 11 shows shale distribution and ore occurrence. Usually thick ore bands occur underlying shale portions, a fact which can be interpreted in at least two ways as will be shown in a later section. Fluorite also occurs between the breccia fragments.

As will be discussed later, the absences of the greenish shale in the periphery of the collapsed (or slumped) zones are significant for the formation of these zones.

Figure 12 shows an example of collapse of the Rosiclare sandstone into the underlying shale occurring at 100 m southwest of the shaft. Purple fluorite occurs in between the broken shale fragments.

Figure 13 shows merismitic fabrics of collapsed limestone occurring at the intensive breccia zone, northeast of the shaft. The size of this elliptical-shaped breccia zone is about 50 m x 150 m, shortest and longest axis respectively. The known vertical extension is about 15 m. The exact downward extension is not yet known.

In both cases of the Sub-Rosiclare and the Rosiclare-Fredonia contact zones, the matrix of the breccias contains fluorite.

The thicknesses of the ore bands are variable; they are about 50 - 100 cm in general. Locally, barite-bands occur with fluorite bands.

Figure 14 shows typical fluorite layers which contain fractured layers of greenish shale and carbonate.

A number of lenticular vugs in the host rock filled with carbonate sand, sphalerite, quartz, and fluorite occur. The inner side of these vugs is generally covered with the euhedral crystals of purple fluorite, sphalerite, calcite, and galena (only at the Sub-Rosiclare horizon). Also petroleum is stained over the fluorite crystals in druses.

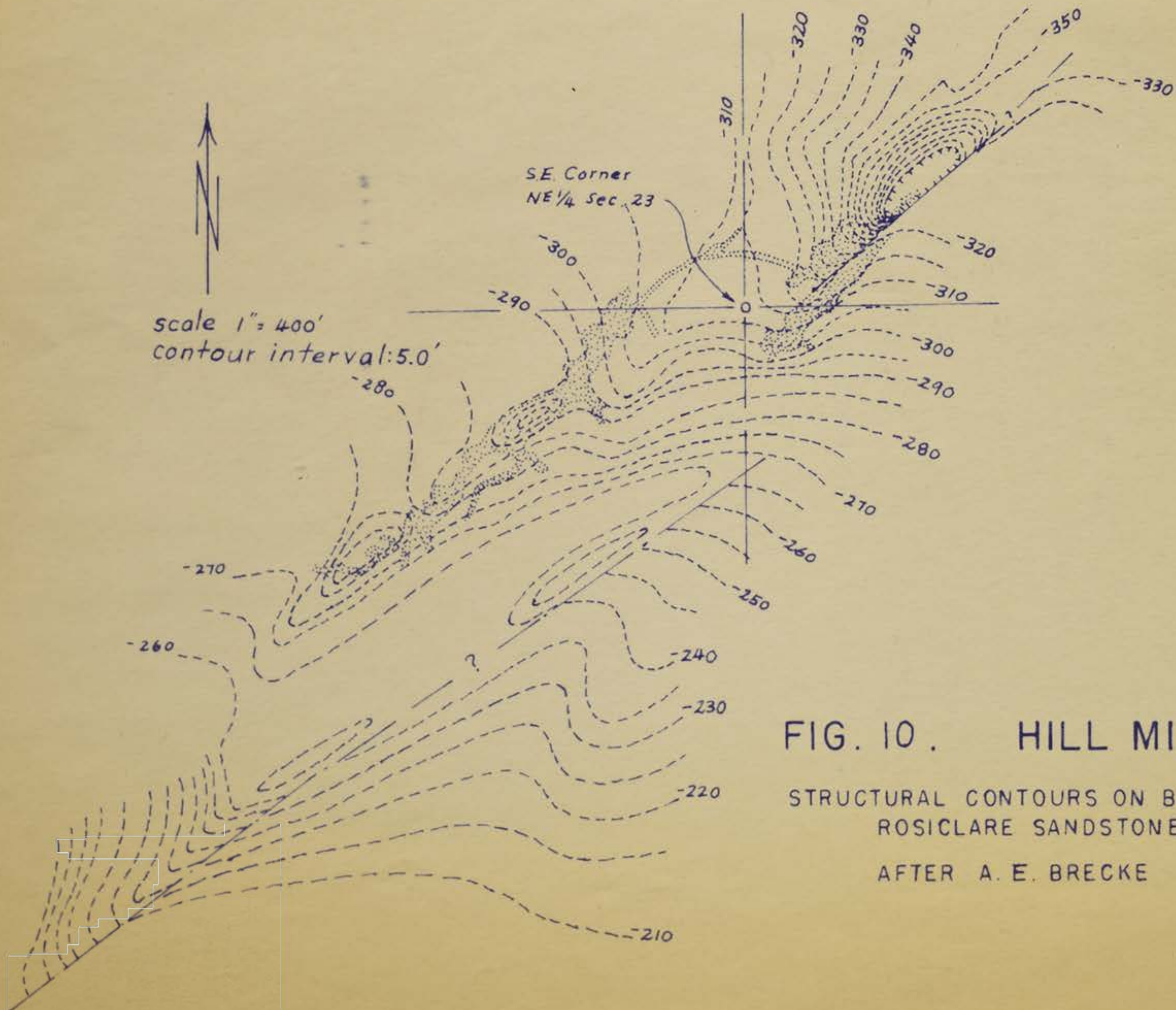


FIG. 10. HILL MINE

STRUCTURAL CONTOURS ON BASE OF ROSICLARE SANDSTONE

AFTER A. E. BRECKE

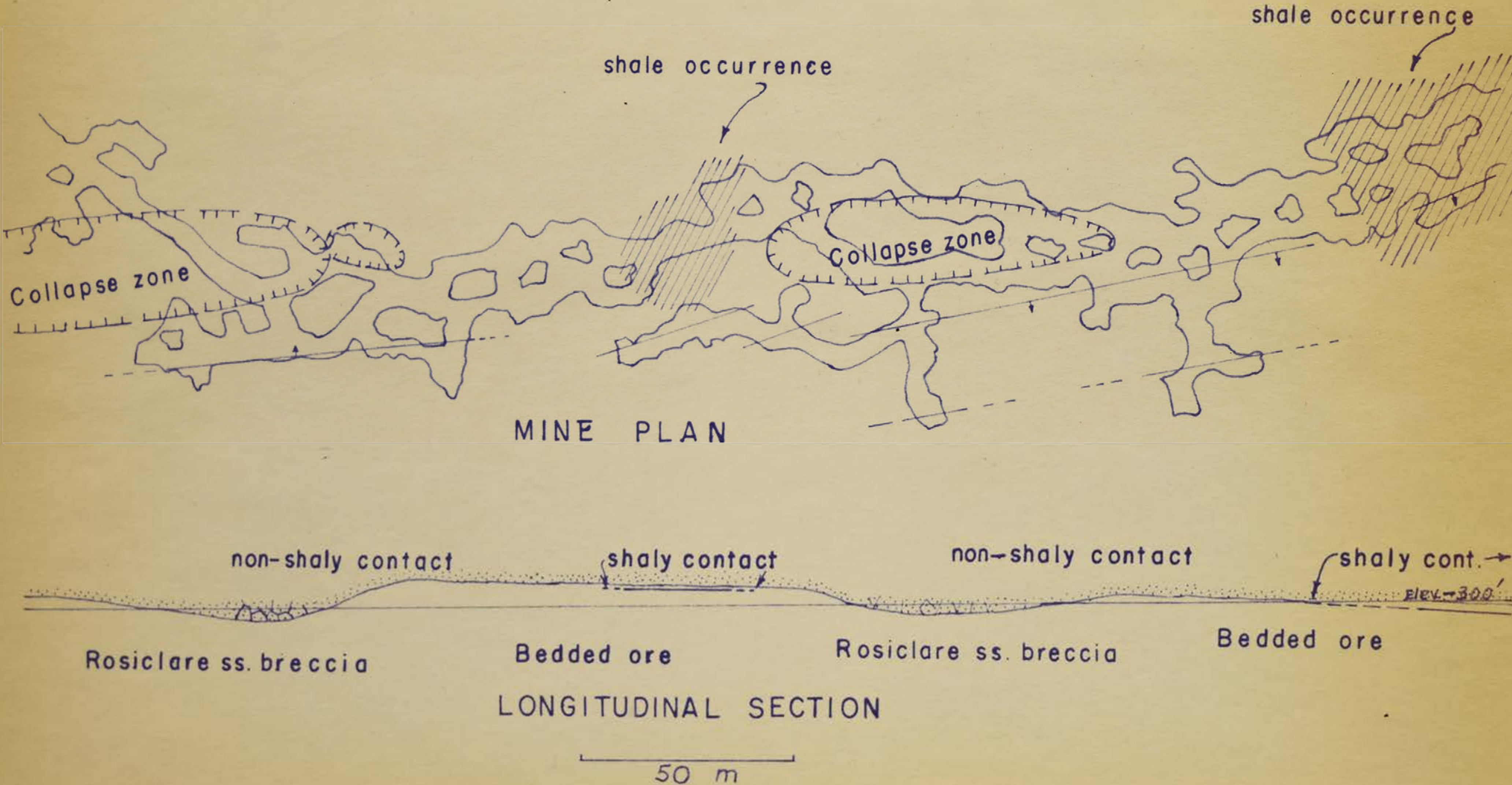


FIG. 11. SHALE DISTRIBUTION & ORE OCCURRENCE, HILL MINE
(According to Mine Maps of the Ozark - Mahoning Co.)

Fig. 12. Rosiclare sandstone block in the underlying shale.

Fig. 13. Breccias of Rosiclare sandstone and Fredonia limestone with chaotic fabrics. Matrix is purple fluorite.

Fig. 14. Typical fluorite band from the Hill mine (Rosiclare-Fredonia contact zone). Black and white layers are fluorite. Sample to the left consists of fractured and broken carbonate. Sample to the right, the broken greenish shale layers occur in the ore bands.

2. Oxford mine

In the Oxford mine two stratigraphic horizons are productive; i.e., the Rosiclare-upper Fredonia and the Bethel-Renault contact zones. Observations were mainly made in the Bethel-Renault contact zone along which the main haulage way is developed in a N. 50° E. direction. The ore bodies occur as parallel blankets along normal faults and pinching out laterally away from these faults.

One of the faults with a displacement of about 4 m and with a strike and dip of N. 50° E. and S. E. 80° cuts through the Rosiclare-Fredonia horizon. Ores are mined along this fault zone. Its continuation to the Bethel-Renault horizon, which is 37 m above the Rosiclare-Fredonia contact, is observed at about 200 m east of the shaft. This fault here is also filled with a small amount of brecciated greenish shale and sandstone, with a matrix of massive fluorite and barite. The thickness of the ore filled into this fault zone is about 50-100 cm.

A normal fault with a displacement of about 2 m is observed at the Bethel-Renault horizon and is filled with some sub-angular carbonate rock and massive yellow fluorite.

The basal sandstone of the Bethel formation dips about 1 to 2° towards N. W.

The mineralogical difference in this mine compared to the others is the abundance of barite. Barite occurs as bands or massive patches in the fluorite layers. Figure 15 shows an example of a fault zone and host rock containing fluorite and barite.

Figure 16 shows barite and fluorite matrix of sandstone megabreccia seen 1 m above the Bethel-Renault contact. The sandstone layer above this collapse structure is not disturbed at all.

A number of broken and disoriented ferroan dolomite veins were frequently observed. Figure 17 shows an example of broken veinlets occurring 60 m southwest of the shaft. The broken pieces of the vein at zone A on Figure 17 are coated or surrounded with thin layers of greenish shale. The matrix filling zone A is argillaceous dark material with disseminated sphalerite grains.

Figures 18 and 19 show the typical barite bands with yellowish fluorite bands, photographed at the Bethel-Renault and Rosiclare-Fredonia horizon respectively.

Figures 20 a and b show a "U" shaped structure of cross-beds of fluorite which has formed in four separate lithologic units. There is neither fault nor shear fracture at the center of this "U" shaped structure. As shown on Figures 20 a and b, the orientation of bands of each unit is independent of the banding in the other units. Between each unit there are thin argillaceous layers with slight grooves.

3. Deardorff mine

In this mine the zone below the Sub-Rosiclare-lower Fredonia contact is the productive horizon.

Figure 21, modified from A. E. BRECKE (1961, personal communication) shows structures and ore occurrence of the mine.

Faults and fractures are generally striking in a N. 40° - 60° E. direction. Two normal faults with a displacement of about 2 m are occurring at the northeastern part of the mine. The rest of the structures appearing on the maps (Figures 21 and 22) are fractures without displacement. The aforementioned two faults are filled with massive fluorite, calcite, and rarely with galena. Also, the continuations of these faults at the Rosiclare-Fredonia horizon seen at a raise are filled with massive yellowish fluorite differing from that at the lower Sub-Rosiclare horizon.

Fractures are generally filled with thin bands of calcite and/or quartz which are thinning upwards. The significance is that these fractures do not extend downwards beyond the bottom of the ore zone. Apparently many of the fractures on the map (Figures 21 and 22) are not "channel ways" of the ascending mineralizing solution(s), as believed by some.

Ore bands occurring in this mine are locally called "coontail" ore which, in cross section, appears to consist of alternating thin layers (av. thickness of a layer measures about 1 cm) of fluorite, sphalerite, and sometimes galena. Seen in three dimensions, the "coontail" layers consist of plate-like masses of the ore minerals.

These alternating "coontail" layers of the ore minerals, because of their unusual texture, have been the subject of much discussion.

The vertical thickness of the "coontail" ore bands (zones) in the mine varies from 0 to 5 m.

The "coontail" and/or ore bands may be classified into three groups, according to their mineral content. They are: fluorite-sulfide ore, quartz-fluorite-sulfide ore, and quartz-sulfide ore. These three classes of ores occur in different positions. Generally the fluorite-sulfide (sphalerite) ores ("coontail") occur at the bottom of the ore zone and the quartz-sulfide ores occur in the upper part of the ore zone. The quartz occurring highest in the ore zone does, in a sense, not behave in the same way in which the term "coontail" is normally used. Significant is the occurrence of the quartz (as banded, massive, or associated with brecciated carbonate) which almost always is located at the central top of the ore zone. Usually druses are seen inside the quartz bands. The inner sides of the druses are frequently stained with petroleum.

The carbonate breccias enclosed at the upper part of the siliceous zone are angular to sub-angular with an average size of the fragments of 1 to 5 cm in diameter.

The aforementioned three classes of ore bands are usually cross-bedded and overlap each other. The overlapping does not necessarily occur between different classes, but may be found in between the bands of the same class with a slight mineralogical or textural difference.

Galena crystals are closely associated with sphalerite.

Figure 22 shows the detail structures and the occurrence of three classes of the ore zone near the shaft. The zone of ore bands in each different class is distributed in a unit, parallel to the N. - E. direction, same as the fractures. Ore bands are pinching out laterally, away from the intense fracture zone.

Figures 23 and 24 show typical "coontail" ores of fluorite and sphalerite.

Figure 25 is an enlarged one-to-one photograph of a thin section made from the "coontail" ore of fluorite and sphalerite.

Figures 26 a and b show a so-called "V" structure of the ore which is a rather typical and representative small structure in the Deardorff mine. As shown on the Figures, one large "coontail" zone, to the right from a fault with a displacement of 25 cm, and two small disseminated sphalerite zones, to the left from the same fault, are laterally pinching out. Also, the occurrence of vugs in the sphalerite zone is typical and representative. The euhedral sphalerite grains are crystallized over the inner side of the vugs facing towards the empty space with their crystal surfaces. Several stylolitic seams are disappearing near the disseminated sphalerite zones.

Figure 27 shows massive and congruent beds of sphalerite and fluorite occurring at the central area of the asymmetric syncline, northeastern area of the mine.

Figure 28 shows the basic configuration of the occurrence of a siliceous brecciated zone above the fluorite-sulfide ore class.

Figures 29 and 30 show typical "overlapping" cross-beds of fluorite and sphalerite.

Figure 31 shows a sequence of several cross-bedded "coontail" bands. Each one of the "units" of cross-beds consists of different minerals.

Figures 32 and 33 show typical occurrences of quartz in the mine.

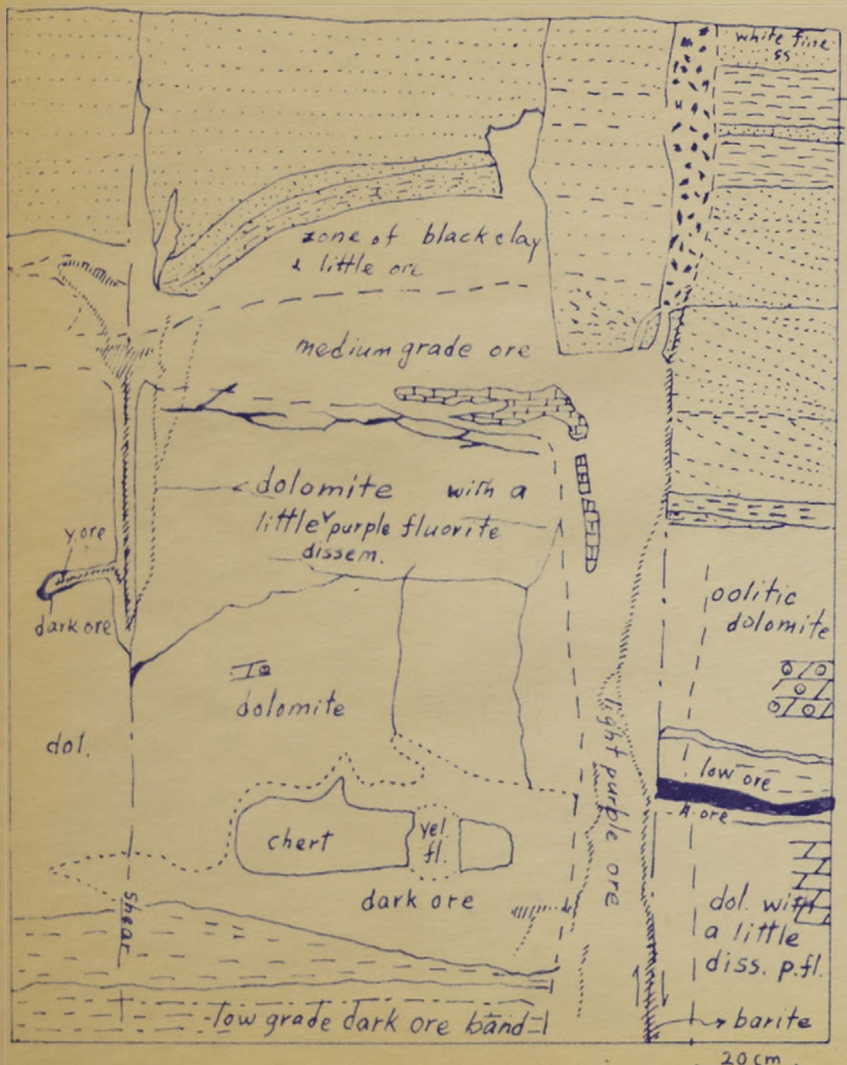


Fig. 15. Vertical fault zone with fluorite ore occurring near it. Location: 30 m southeast of the shaft of the Oxford mine.

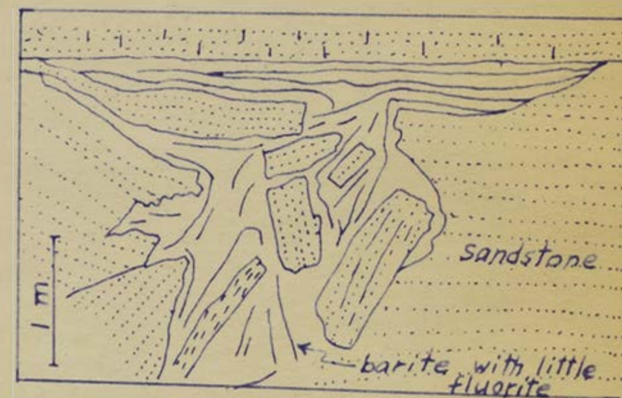


Fig. 16 . Barite and fluorite as the matrix of gray sandstone mega-breccia, 1 m above the Bethel- Renault contact and above the dolomite - fluorite ore bed. Note contorted barite bands.

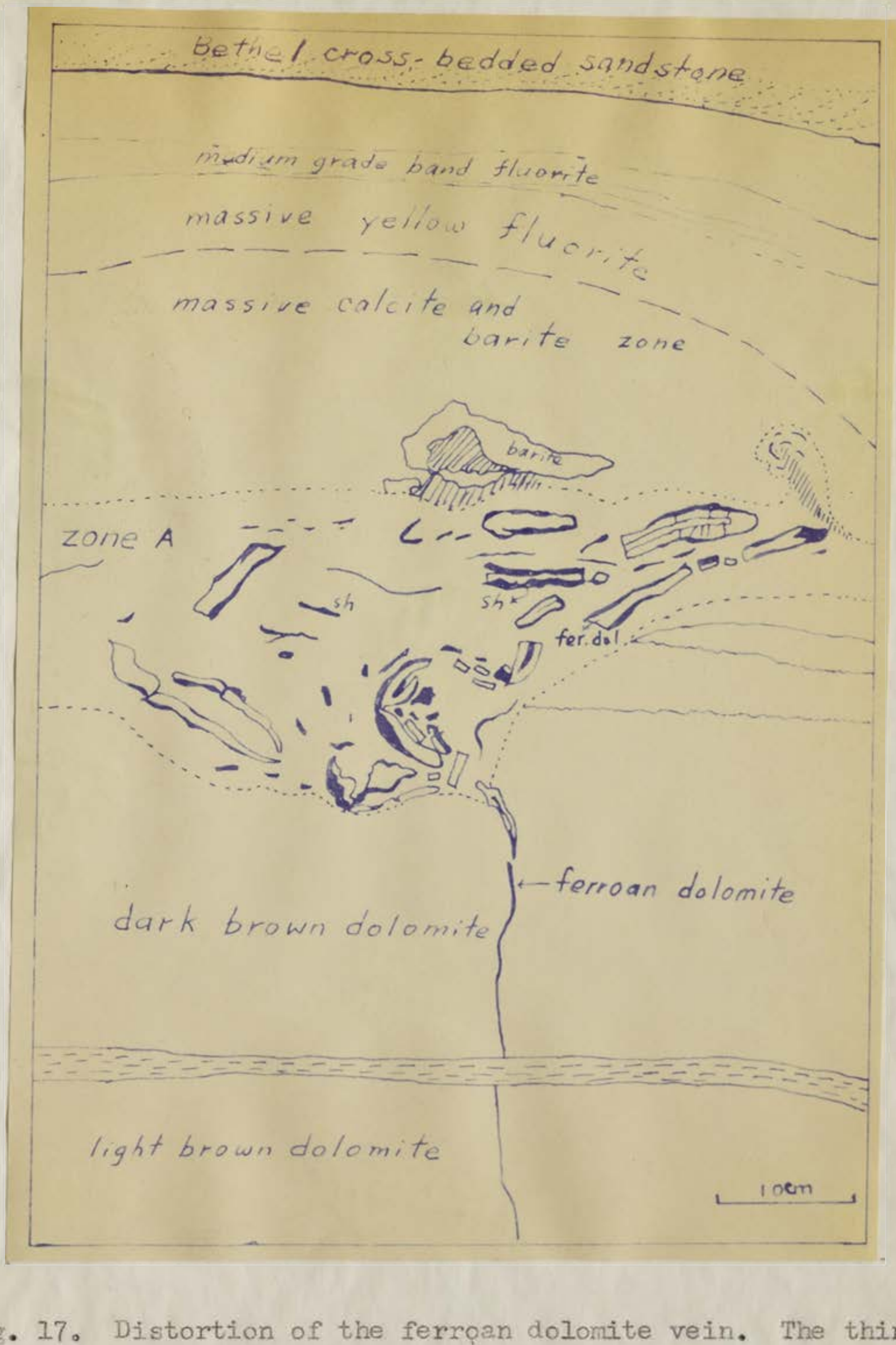


Fig. 17. Distortion of the ferroan dolomite vein. The thin layers covering the broken pieces of ferroan dolomite are shale. The material filling Zone A is argillaceous with disseminated sphalerite. The areas of inclined lines at the center are loose argillaceous carbonate material with disseminated sphalerite.

Fig. 18. Typical colloform bands of barite (white, thickness is about 2 cm in av.) along the rims of fluorite bands (grey), 1 m below the base of the Bethel formation. The white piece of paper to the lower right measures about 12 cm.

Fig. 19. Barite (white) and fluorite (yellow) bands occurring at the Rosiclare and Fredonia horizon of the Oxford mine. Dark beds are low grade fluorite bands. Scale is indicated by hammer at the bottom center.

Fig. 20 a. Four units of cross-bedded fluorite beds in "U" shaped channel below the undisturbed base of the Bethel formation, about 60 m southwest of the shaft of the Oxford mine.

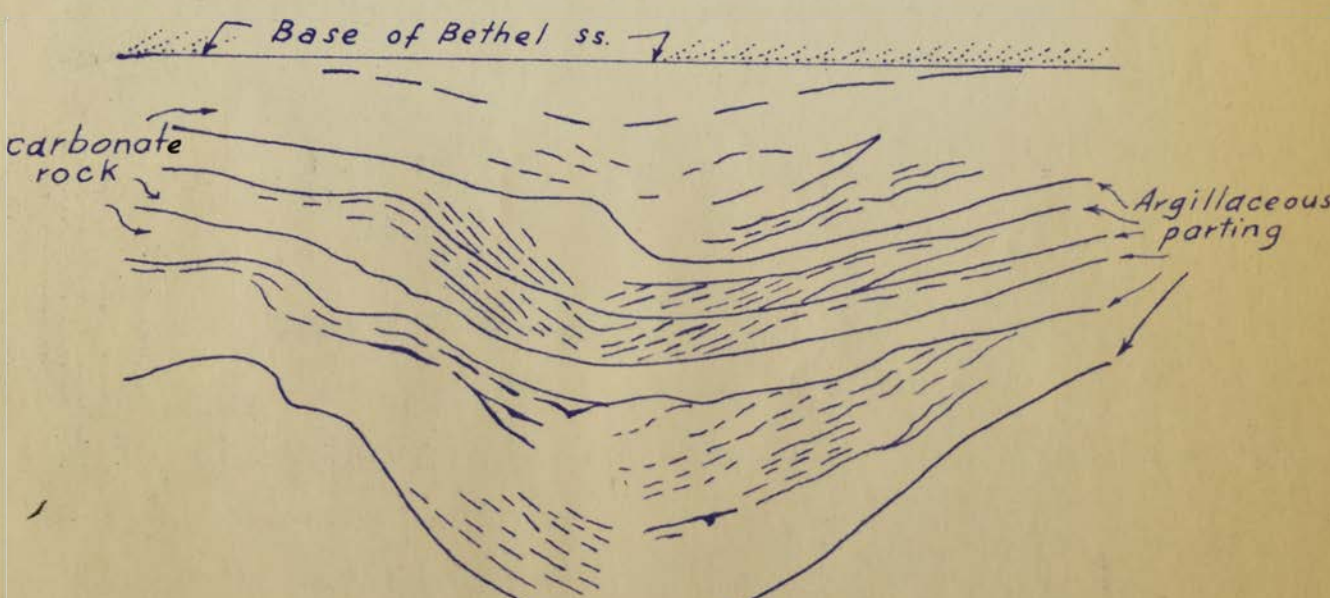


Fig. 20 b. Drawing of Figure 20 a, showing four units of cross-bedded fluorite bands.

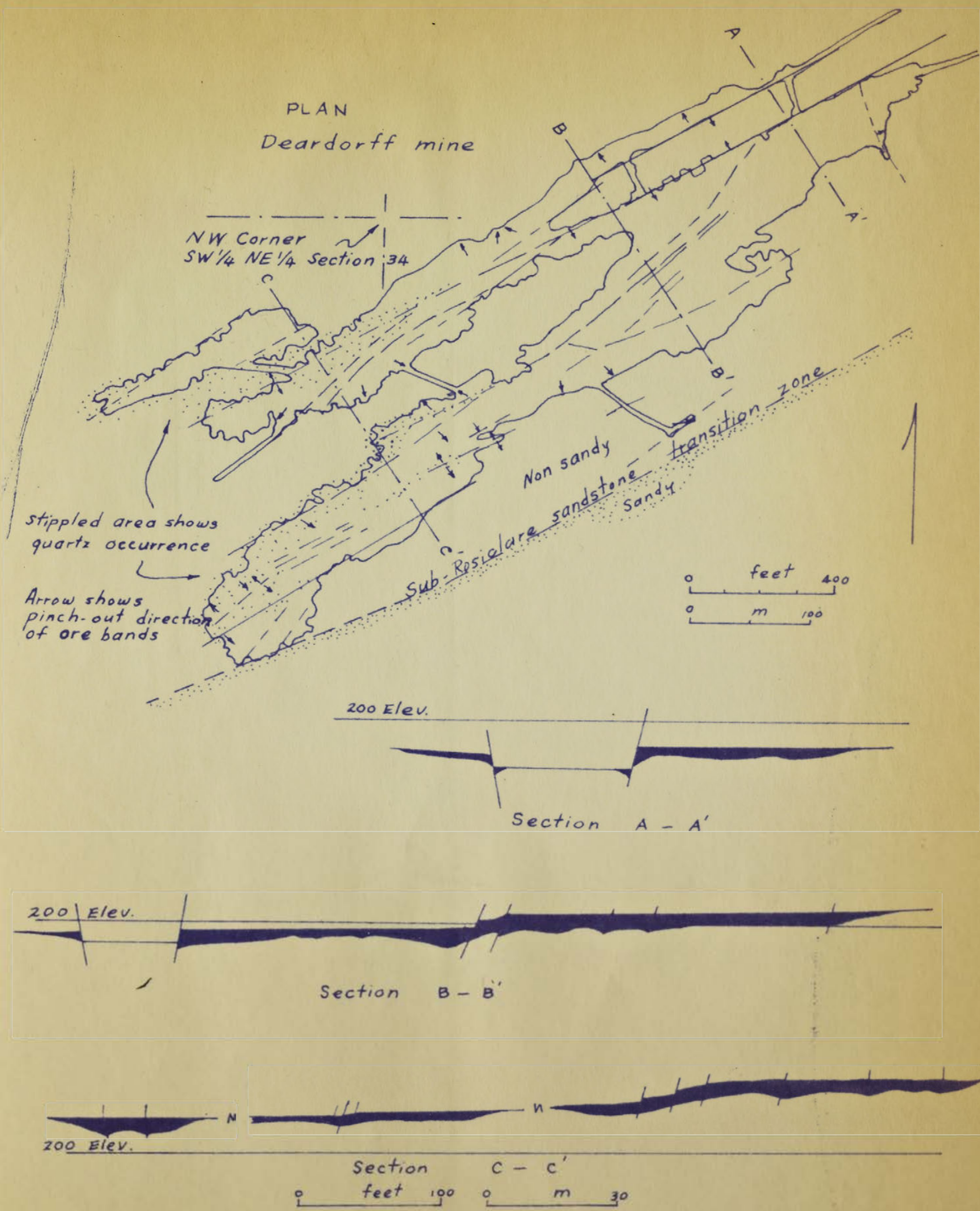


Fig. 21 . Structure and ore occurrence of the Deardorff mine. Modified from A.E.BRECKE (1962, personal information).

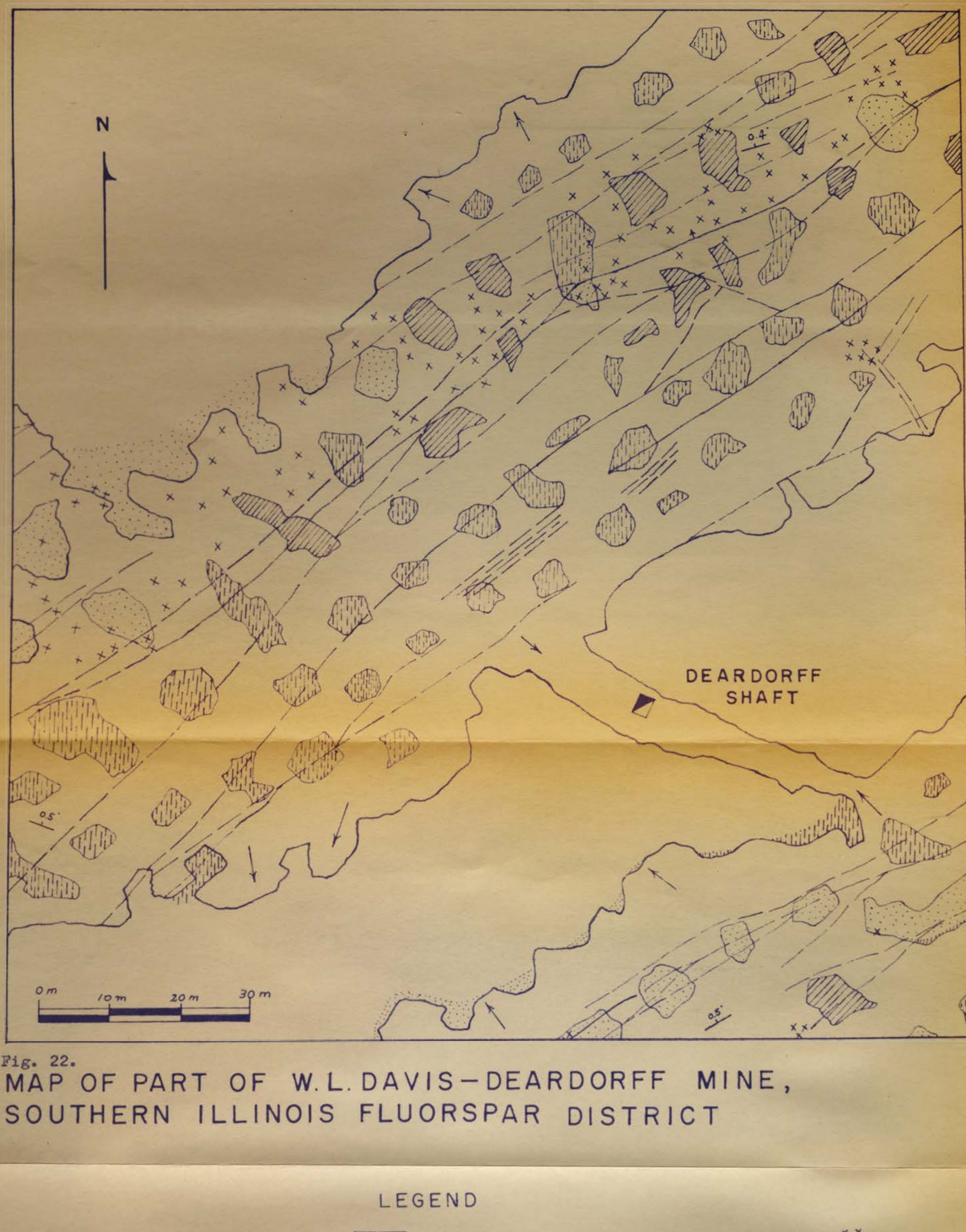


Fig. 22.
MAP OF PART OF W. L. DAVIS–DEARDORFF MINE, SOUTHERN ILLINOIS FLUORSPAR DISTRICT

LEGEND

SPAR-SULFIDE ORE
QUARTZ-SPAR-SULFIDE ORE
QUARTZ-SULFIDES ORE
MINOR FAULT
FRACTURE
HIGHLY SILICEOUS BRECCIATED AREA
PINCHED-OUT DIRECTION OF ORE BANDS
STRIKE AND DIP OF DOLOMITE
PILLAR
LIMIT OF MINED AREA

Fig. 23. Typical "coontail" ore of fluorite and sphalerite, left sample. Note the druses at the center of the fluorite layers (white). They are stained with petroleum. To the right, the sample shows rather thick masses of layered fluorite (light grey). The mark "Sub - R" on the top is the contact between the upper and lower Fredonia limestone. Deardorff mine.

Fig. 24. Typical "coontail" ore bands. The bands above the central line consist of fluorite (white) and low grade fluorite bands (black) with a few sphalerite bands (grey). The bands below the central line consist mainly of sphalerite (grey) and low grade fluorite bands (black) with a few high grade fluorite bands to the lower left. The white piece of paper at the center measures about 12 cm. Pillar 128, Deardorff mine.

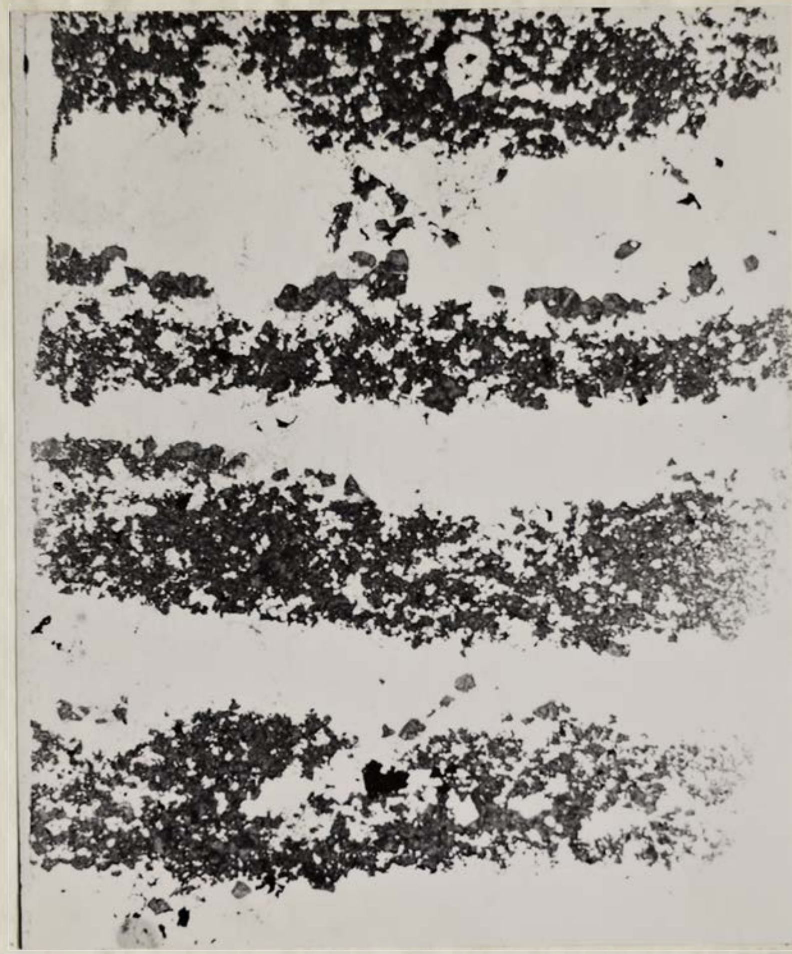


Fig. 25. Enlarged direct one-to-one photograph of a thin section of "coontail"ore. Grey spots are sphalerite and white is fluorite. Galena grains (black) occur inside the sphalerite bands. However, in a few cases, subhedral galena occurs between fluorite crystals in the main fluorite bands. A considerable number of euhedral quartz grains (av. length = 0.1 mm) occur inside the sphalerite band and in the fluorite crystals. The base of the photograph measures about 2.2 mm.

Fig. 26.a. A typical and representative "V" structure. The "coontail" ore of galena and fluorite is pinching laterally away from the fault zone which is the vertical line to the central left. See the detail drawing on the next page. 30 m northwest of Pillar no. 99, Deardorff mine.

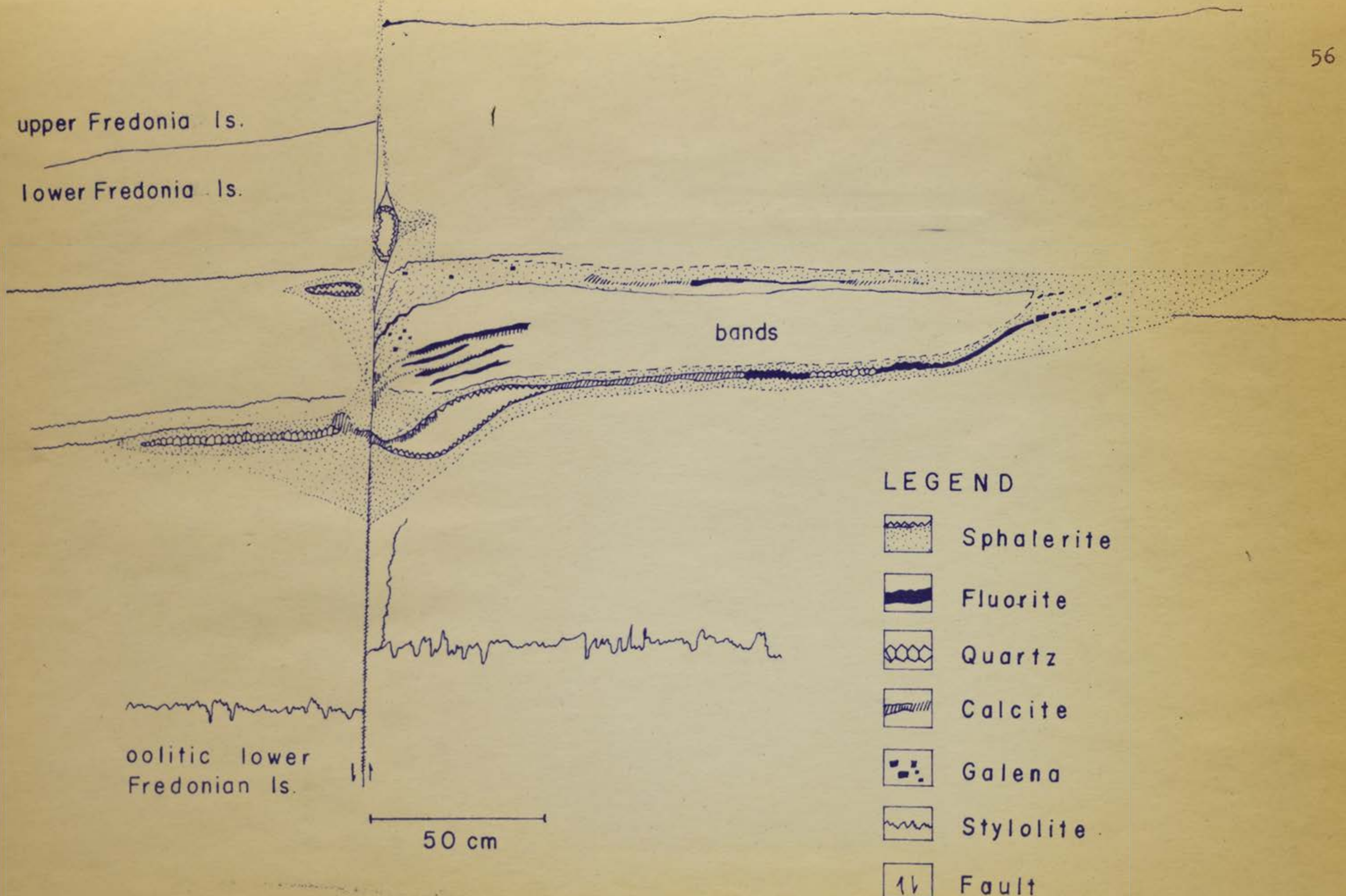


Fig. 26 b. A typical and representative small "V" structure. This drawing corresponds to Figure 26 a.

Fig. 27. The congruent and massive sphalerite (brown) and fluorite bands (white). A galena band occurs to the lower left inside the sphalerite zone. Pillar no. 69, Deardorff mine. The scale is given by the hammer.

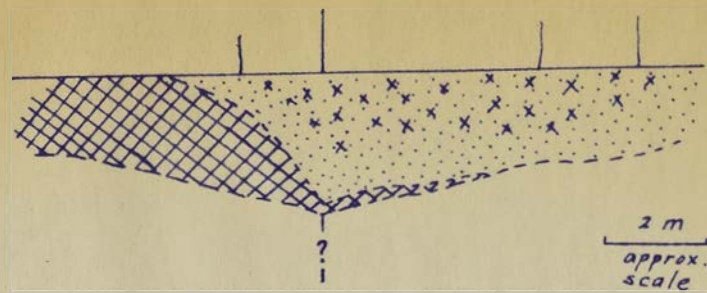


Fig. 28. Basic configuration of the ore zone of a siliceous brecciated area in the Deardorff mine. Cross-lined portion is a zone of the fluorite, sphalerite, and galena bands; dotted portion is siliceous zone. Cross-marks indicate brecciated and disoriented zone of siliceous carbonate.

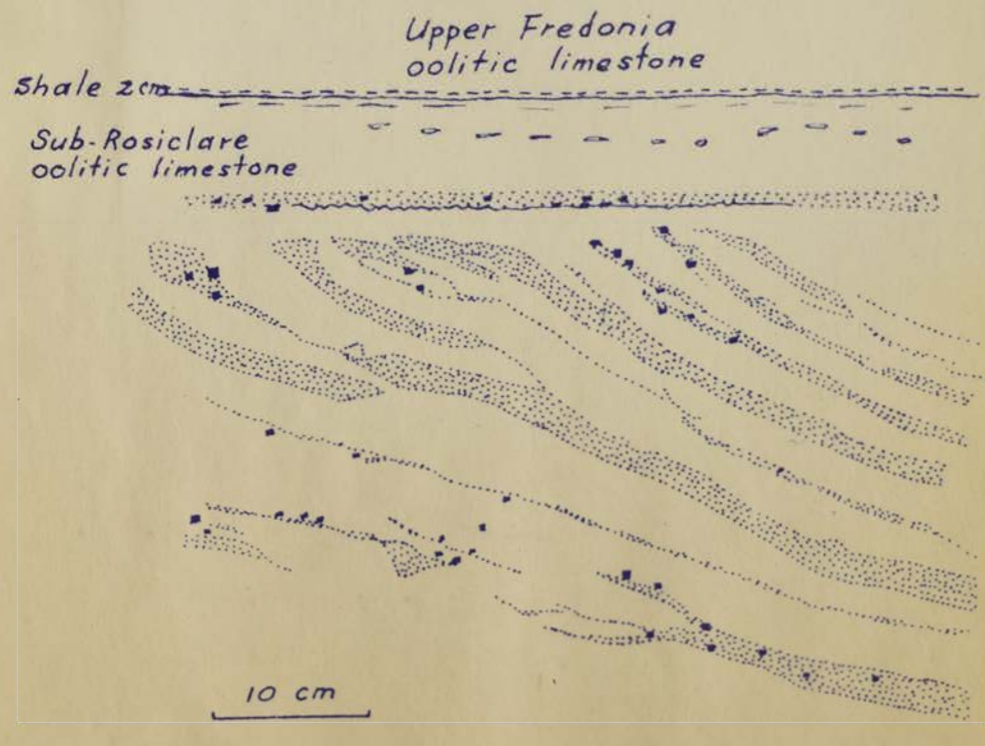
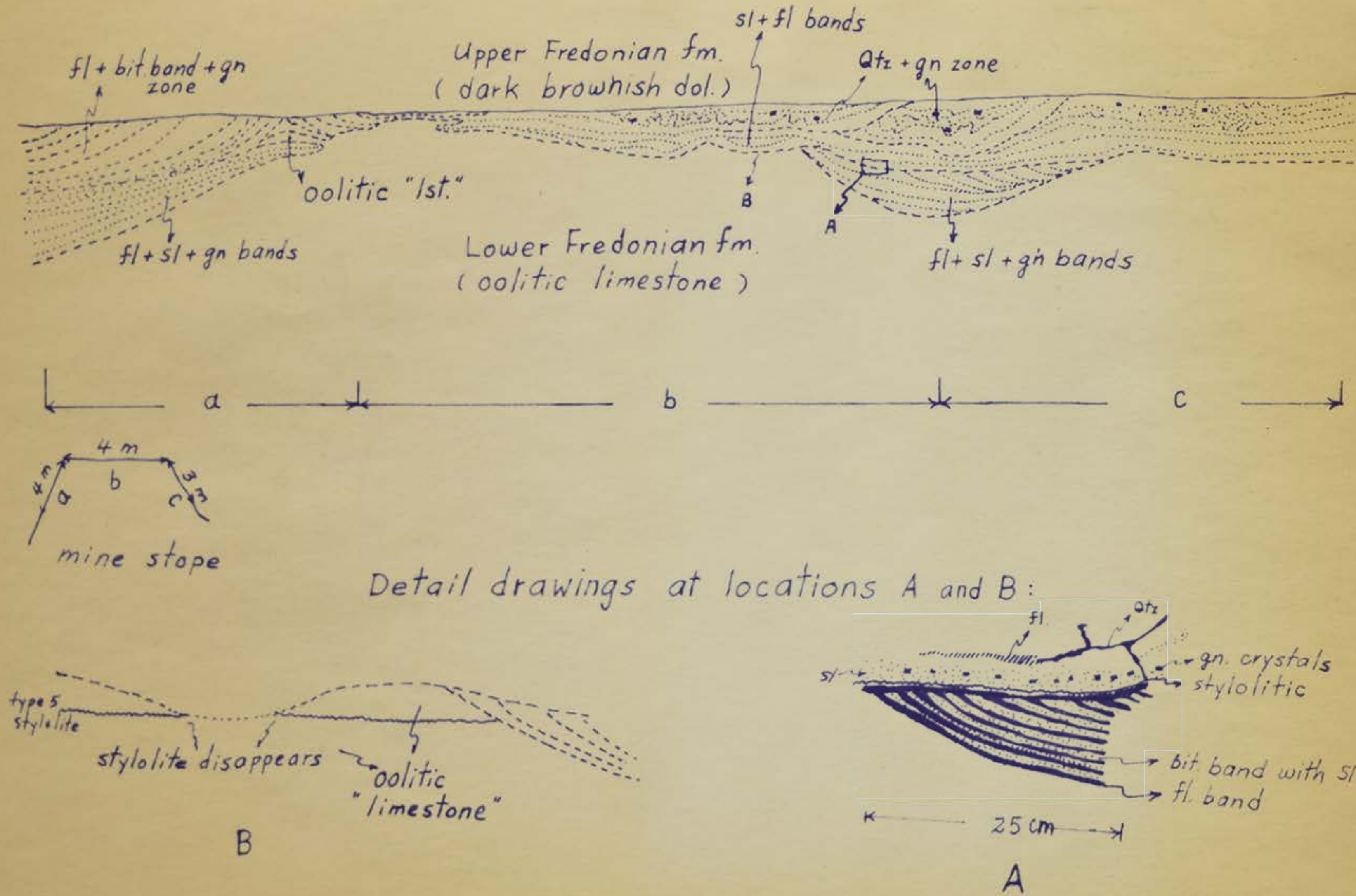


Fig. 29. Cross-beds of sphalerite (dotted) and fluorite (white ground) occurring below the base of the upper Fredonia limestone. Cubes are galena crystals. 30 m northwest of pillar no. 79, Deardorff mine.

Fig. 30. The superimposed cross-bands or cross-bedding of fluorite and sphalerite. Pillar no. 89, Deardorff mine. Scale: The thickness of the thinner bands in the lower half of the photograph is 2 cm on the average, (Photo A. E. BRECKE).



fl: fluorite, sl: sphalerite, gn: galena, Qtz: Quartz, bit: bituminous.

Fig. 31. OVER-LAPS OF ORE BANDS, 10 m SOUTH OF PILLAR No. 71, DEARDORFF MINE, SOUTHERN ILLINOIS FLUORSPAR DISTRICT

Fig. 32. Typical occurrence of a brecciated siliceous zone. Note that the lower portion of the zone is banded whereas the upper portion is rather contorted and does not show regular banding. Also note that the oolitic limestone below this zone is stained dark. Picture is taken at Pillar no. 11, S. W. end of the Deardorff mine. Scale given by hammer.

Fig. 33. Quartz bands with druses in them. Dark and brown bands are sphalerite. The white piece of paper to the upper right measures about 12 cm. Picture is taken at Pillar no. 62, Deardorff mine.

CHAPTER VI. STYLOLITES AND RELATED SEDIMENTARY STRUCTURES

A. Introduction

There are a few minor, yet important, geologic phenomena for which the explanations are unsatisfactory, leaving their solution still in a puzzling state. The explanations of these phenomena are controversial. One of these is the stylolite.

Since the middle of the eighteenth century, more than one hundred and twenty articles on stylolitic seams (lines) have discussed this topic in various publications. The occurrences of stylolites in sedimentary rocks have received attention from geologists from the standpoint of curiosity, relation to diagenesis, stratigraphy, economic (mineral deposits) significance and general sedimentary or structural interest.

Stylolites consist of two interlocking, alternating, or mutually interpenetrating surfaces marked by a thin black seam (see Figures 34 and 35). The toothlike projections of one side fit into sockets of like dimension on the other. The stylolitic surface itself is usually marked by a thin seam of clay or black material. Generally the thickest clay portion or cap occurs at the crest or valley of the stylolitic seam with the side of the column having grooves, striations or slickensides.

The length of the socket-like or columnar projections varies from a fraction of a centimeter to more than 50 centimeters. The width of a stylolite or columnar projection is as variable as its length. In cross section, a stylolitic surface resembles a type of zig-zagging or suturing, depending upon the pattern type, as discussed later. The stylolitic surface

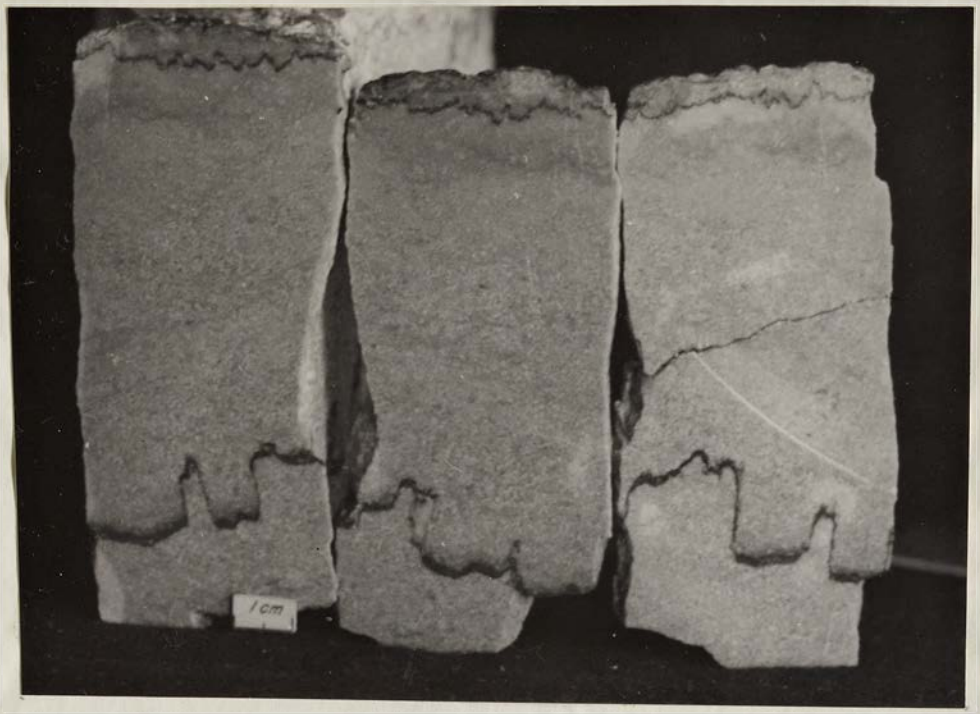


Fig. 34. Up-peak type stylolite from the Fredonia limestone, Southern Illinois. Figure 41 is a side picture of these cuts.

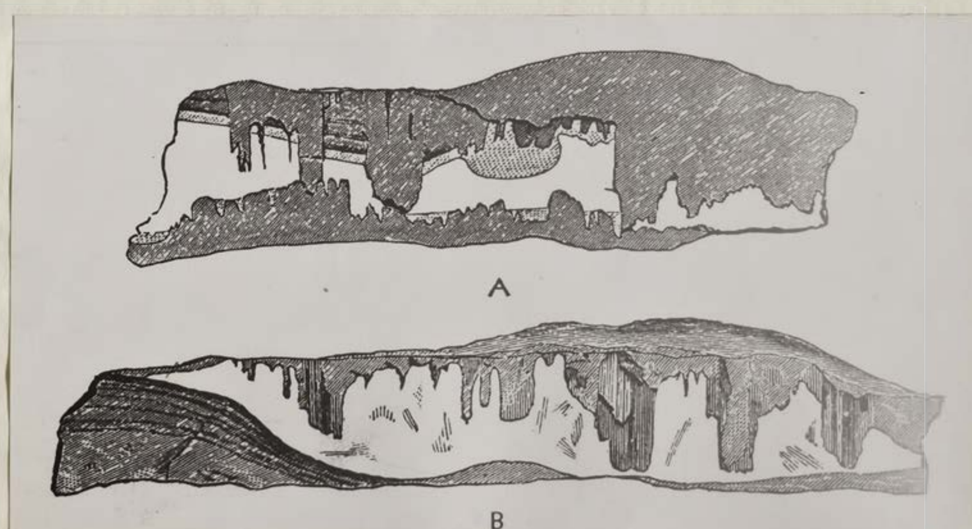


Fig. 35. Specimens of stylolitic Devonian limestone from Port Dover, Canada. The stylolitic columns penetrate a mass of chert embedded in the limestone and are best developed on the upper side in B. In A, however, the relation of stylolites to chert is confused by the presence of fragmental chert (stippled) in a thin layer above and below. (LOGAN, 1863, "Geology of Canada", p. 633.) (After SHROCK, 1948, "Sequence in layered rocks", p. 240.)

is traceable for varying distances in the third dimension, and may vary from a few centimeters to hundreds of meters. The stylolitic surface may be located at the contact of two beds with different textures or it may develop in beds of uniform texture. Generally the stylolitic plane is parallel to a local bedding plane. However, stylolites traversing bedding planes have been observed. For a general description of stylolite-geometry, see Appendix I (RUCHIN, 1958).

The glossary of the American Geological Institute (revised edition, p. 283) defines "stylolite" as follows:

> "A term applied to parts of certain limestones which have a columnlike development; the "columns" being generally at right angles or highly inclined to the bedding planes, having grooved, sutured or striated sides, and irregular cross sections."

Stylolitic seams are often very numerous and close together. In a single, thin stratum there have been observed many seams lying directly one above the other with only a few centimeters of rock separating them. They may lie one upon another and even penetrate one another.

Stylolites are well developed in limestones and dolomites. Also they occur in marble, sandstone, ortho-quartzite, gypsum, anhydrite, and salt. HEALD (1955) reports stylolitic seams developed in muscovite, feldspar, colophanite, sphene, tourmaline, zircon and pyrite in sandstones of various localities in the eastern United States. They have been observed traversing chert nodules (HUNT, 1863; EASTIN, 1933; TREFETHEN, 1947). MAIES and GOLDING (1961) believe that suture-lines between asbestos in veins may also be called stylolites.

In the course of this investigation, the author observed a tapered and pointed type of stylolites (see Figure 38, type 5 of the Classification of stylolites) developed horizontally to bedding planes of novaculite at a Novaculite Quarry, 3 miles northeast of Hot Springs, Arkansas.

The author also has had a chance to observe thin sections of baritic shale (research materials of R. A. ZIMMERMAN of the Department of Geology, Missouri School of Mines and Metallurgy) from the Stanley shale occurring in the Chamberlain Creek Syncline, Magnet Cove, Arkansas. Here, clay seams which are about 1 mm maximum thickness and parallel to bedding planes show pseudo-stylolitic contacts with barite. In some cases barite lenses in contact with clay seams have microstylolitic contacts along the lower parts. Microstylolites of type 5 (see Figure 38) are found along the bedding horizons. Clay seams may diverge laterally to form two or three separate stylolites.

So far, stylolites have been observed in various sedimentary rock types and supposedly also in some igneous rocks (STOCKDALE, 1922, p. 13, BLOSS, 1954, GOLDING AND CONOLLY, 1960 and 1962) and veins (MAIES and GOLDING, 1961, p. 198).

On the outcrop stylolitic seams in carbonates show effects of differential weathering (see Figure 36). The stylolite itself weathers more easily than the carbonate, which is evidenced by a depression or groove in the rock which coincides with the stylolitic seam. GRIM and LAMAR (1937) report that the clay mineral illite, which generally constitutes the stylolitic seams (THOMSON, 1959), is unstable under weathering conditions, especially in the presence of alkalies such as are often found in limestone. The alteration product is commonly beidellite. The weathered partings may contain either loose materials or remain as open cavities. In addition to the instability of illite, accelleration of the weathering action takes place as the stylolite is further opened on exposure to the migration of groundwater along the stylolitic seam. Possible early migrations of oil along the stylolitic seams were reported by RAMSDEN in 1952.

The name "stylolite" comes from the Greek stylos (στυλος), meaning column and lithos, meaning rock. According to numerous authors, the earliest mention of stylolites appears to have been made by MYLIUS in 1751, who described them as "Schwielen" and did not coin the term "stylolite". FREISELEBEN, in 1807, spoke of the phenomenon as of "zapfenformige Struktur der Flozkalksteine", and HAUSMAN later referred to it as "Strangelkalk" (re. STOCKDALE, 1922, p. 13). The term stylolite was given first by KLODEN (1828, p. 28) who thought the structure to be a distinct species of organism, under the name of "Stylolithes sulcatus". Originally, two German terms, "Drucksuturen" and "Stylolithen", were used as referring to different structures. The term "Drucksuturen" was used more for patterns resembling type 5 in Figure 38, whereas "Stylolithen" was applied more to patterns similar to types 1 to 4, especially 3 and 4 because they really show similarity with columns or "stylos". Later, these two terms came to be used for analogous structures.

The earliest theories regarding the origin of stylolites were quite hypothetical. Most of them are rejected today. Only two, the contraction-pressure theory and the solution-pressure theory, are accepted possibilities by present geologists. The earlier theories which will be briefly discussed in the next sub-chapter are as follows: 1) Organic, 2) Crystallization, 3) Erosion, 4) Gas, and 5) Bitumen theory.

Fig. 36. Differential weathering of stylolites in limestone of the Fredonia limestone. Picture is taken at an outcrop on Illinois State Highway 146, about 2.9 km (1.8 miles) northeast of Elizabethtown, Hardin County, Illinois.

B. Historical investigation on the study of stylolites

Early theories which are perhaps of less value regarding the origin of stylolites, will be mentioned briefly in this sub-chapter. The theories and facts or evidence to support or to object to the two presently accepted theories, the pressure-solution theory and the contraction-pressure theory, will then be discussed chronologically.

Table I is a chronological chart of the theories proposed on the origin of stylolites. Some of the early literature was not available and the information is, therefore, second hand.

Organism theory: EATON (1824), who appears to have been the first to offer an explanation of the structures, considered the stylolitic columns to be of organic origin and named them "lignilite". He believed that these structures were coral columns.

KLODEN (1828), in observing the structures in the Muschelkalk at Ruderdorf, Germany, described them as a distinct species of organism and gave them the name "Stylolithes sulcatus". LEUBE (1850) described these structures as fossil bone structures of ancient organisms. Though KLODEN's name "stylolithes" has been retained for the structure, the organism theory has had few followers.

Crystallization theory: BONNYCASTLE (1831) considered the structure to be a mineral formed by infiltration. This explanation was accepted by VANUXEM in 1838 who named the structures "epsomites" ($MgSO_4 \cdot 7H_2O$) in 1842. This theory was accepted by EMMONS (1842) and HALL (1843) with modification. MEYER (1862) proposed that gypsum might have been the agent of crystallization. ROSSMASSLER and von COTTA (1846) compared stylolites with ice crystals. HUNT (1863) described them as "crystallites" of sodium sulphate.

Erosion theory: PLIENINGER (1852) suggested that the surface of the soft lime ooze was first raised above water and, upon drying, was separated

Table I. Historical investigation on the origin of stylolites.

Investigator	Year[!]	Theory 1[**]	Theory 2[#]	Remarks
MYLIUS	1751			Structure mentioned first
* EATON	1824			Organic theory, "lignilite"
KLODEN	1828			Stylolithes sulcatus, as organic species
BONNEYCASTLE	1831			Crystallization theory
QUENSTEDT	1837		+	
VANUXEM	1838			Crystallization, as Epsomite
* von COTTA	1846			Ice crystal
PLIENINGER	1852			Erosion theory
THURMAN	1857		+	
ALBERTI	1858			Bitumen theory
von MEYER	1862			Crystallization of gypsum
HUNT	1862			As crystallites
* MARSH	1868		+	
ZELGER	1870			Gas theory
* GÜMBEL	1882		+	
FUCHS	1894	+		
* HOPKINS	1897			Erosion theory
* ROTHPLETZ	1900		+	
REISS	1902	+		
* GRABAU	1913	+		

* This literature was read; the papers not available were quoted by MARSH, 1868; HOPKINS, 1897; STOCKDALE, 1922, 1923; TWENHOFEL, 1926; SHAUB, 1939; and others.

** Solution-pressure theory

\# Contraction-pressure theory

! Year given is earliest record of that author's proposal for the origin of stylolites.

Investigator	Year!	Theory 1**	Theory 2#	Remarks
WAGNER	1913	+		
*TARR	1916			Stylolites in quartzite
*GORDON	1918	+		
*STOCKDALE	1922	+		
*TWENHOFEL	1926	+		
*BASTIN	1933	+		
*PRICE	1934	+		Differential solution alone
*CAYEUX	1935	?	?	
*SHAUB	1937		+	
*YOUNG	1945	+		
*TREFETHEN	1947	+		
*SLOSS	1948	+		
*SHROCK	1948		+	
*CONYBEARE	1949	+		
*PROKOPOVICH	1952		+	Subaqueous solution theory
*RAMSDEN	1952	+		
*RIGBY	1953	+		
*HERGENBACK	1953	+		
*DUNNINTON	1954	+		
*BLOSS	1954			in volcanic rocks
*HEALD	1955	+		
*RUCHIN	1958		+	
*THOMSON	1959	+		
*HEALD	1959	+		principally during diagenesis
*BROWN	1959	+		
*ILLING	1959		+	
*GOLDING et al	1962			in volcanic rocks

into blocks by shrinkage-cracks. These cracks were later altered by the action of rain drops, thus producing the stylolitic columns. After subsidence, the holes or columns would gradually be filled by later sediments. This theory was also followed by QUENSTEDT (1853), WEISS (1868), HOPKINS (1897), and RINNE (1905).

HOPKINS (1897) observed that stylolite seams in the Salem limestone in Indiana were parallel to bedding planes. It appeared to HOPKINS that the erosion theory of the origin of stylolites was ambiguous, since he states in 1897 (p. 143) that: "It is quite probable that they have been caused by different agencies. Some may be mud cracks, some may be due to the action of rain or spray on the exposed surface and....by the escape of gases from the limestone mud."

Gas theory: ZEIGER (1870) attributed stylolite formation to the escape of gases through the soft plastic sediment and subsequent filling of the passage ways. This theory was followed, with modification, by HOPKINS and SIEBENTHAL (1897) and POTONIE (1910).

Bitumen theory: ALBERTI (1858) suggested that the columns were formed by drops of petroleum pushing their way upward in the sediment which was still in a soft, viscous state.

Solution-pressure theory and contraction-pressure theory: After the year 1900, as shown on Table I, only two controversial theories remained. The two theories, the solution-pressure theory and the contraction-pressure theory, have been debated by geologists, since the turn of the century to the present time. The solution-pressure theory has been the more often accepted.

The contraction-pressure theory, briefly, states that stylolites are a result of the differential compression of sediments while in the soft plastic state. It was first postulated by QUENSTEDT (1837 and 1861) and was followed by THURMANN (1857), MARSH (1867), GÜMBEL (1882, 1888), ROTHPIETZ (1900), SHAUB (1937, 1949, 1950, 1953), TREFETHEN (1947), RUCHIN (1958), and by others.

The solution-pressure theory, i.e. that the stylolites are a result of the differential chemical solution under differential pressure after the lithification of sediments, was suggested first by FUCHS (1894) and was followed by REISS (1901), WAGNER (1913, 1914), GORDON (1918), STOCKDALE (1922, 1923, 1926, 1936, 1939, 1941, 1943, 1945), SLOSS (1948), HEALD (1955), THOMSON (1959), and by others.

QUENSTEDT (1837, 1861; STOCKDALE, 1922, p. 25) suggested that the stylolites develop through differential pressure of two adjacent sedimentary units; the two beds exhibit different degrees of resistance to compaction at the time of compaction, because of the different times of their deposition. THURMANN (1857) advocated QUENSTEDT's theory.

After extensive work on stylolites in the Clinton limestone in Lockport, New York, MARSH (1868) suggested that the stylolitic displacement took place before lithification. It was assumed by him that a thick bed of fine grained lime carbonate was deposited and the remains of organisms, such as shells, were then scattered over the ooze. This ooze was then covered by a very thin layer of argillaceous mud, upon which was deposited more calcareous mud. As a result of the resistance offered by the shell or other organic substance, "the surrounding material will be carried down more rapidly, thus leaving a column projecting above, each protected by its (clay) covering and taking its exact shape from its outline" (MARSH, 1868).

GÜMBEL (1882) made an experiment to produce artificial stylolites.

FUCHS (1894, 1896) was the first to suggest the solution-pressure theory. He came to the conclusion that (1) they are formed in hard rock by chemical solution under pressure; (2) the clay cap is the insoluble residue of the dissolved substance; (3) the polished and striated sides of the columns are a result of movement; (4) so called "Drucksuturen" is a special form of stylolites. He reported also traverse stylolites and broken fossils inside the stylolitic columns (STOCKDALE, 1922, p. 29-30).

READ (1895) reported stylolitic contacts between quartzite pebbles in the Bunter conglomerate of Cannock Chase, England and concluded that the pitted pebbles are the result of contact solution.

The contraction-pressure theory by MARSH and GÜMBEL was supported and discussed by ROTHPLETZ (1900) in various aspects. He suggested that the differential and irregular hardening of the plastic mass (lime ooze) brought about by the cementing medium is related to the differential compression of sediments to produce stylolites. He pointed out that stylolites give no indications pointing to any sort of essential chemical activity and stylolites may also form an oblique or horizontal direction due to a pressure other than vertical (STOCKDALE, 1922, p. 28-29). ROTHPLETZ (1900; re. STOCKDALE, 1922, p. 15-16) differentiated between "Drucksuturen" and "Stylolithen". The latter he thought to have formed in a mud, the former solid portions, such as pebbles or fossils.

REISS (1902), after a study of stylolites in the Muschelkalk of Germany supported FUCHS' pressure-solution theory with the following evidence: (a) partially dissolved fossils in stylolitic columns, (b) clay caps of traverse stylolites, and (c) striations on the sides of the columns. He also considered that cone-in-cone structures may have an origin similar to that of stylolites produced in hard rock. GRABAU (1913) followed the solution-pressure theory.

WAGNER (1913) made an extensive study on the structures of stylolites in the Muschelkalk of Germany. He cited the difference between "Drucksuturen" and "Stylolithen" in that these phenomena are only a matter of size and form; there are no sharp distinctions between them. He supported the solution-pressure theory with the following evidence: (a) Mussel and brachiopod shells are pierced by stylolites; (b) younger stylolites penetrate older ones; (c) the clay cap is the solution residue, etc. The size and form of stylolites depend upon the rock. He referred to RIECKE's principle (1895) for the differential solubility throughout the one horizontal bed due to the extreme differential pressures. Bent or curved stylolites were observed and explained as due to a complicated pressure and solution factor.

TARR (1916) reported the first stylolites in the Dakota quartzite from northeast of Lincoln, in French Gulch, Colorado, without considering the origin.

GORDON (1918) claims the solution-pressure theory as being the dominant one in the origin of stylolites in the Ordovician Tennessee marble near Knoxville. According to his observations, the stylolites, in general, are approximately parallel with the bedding planes, whereas at some places they are oblique or vertical to the bedding planes. On page 564, he notes that "... where the structure is right angle, distinct columns are wanting, the suture appearing as a wavy or zig-zag line."

In the present investigation, the author observed that the stylolites in the Tennessee marble in Parker Hall, the administration building of the Missouri School of Mines and Metallurgy, are almost parallel to the direction of foliation. Most of the stylolites are of type 5. (see the Geometric classification of stylolites, Figure 38) in that they have small amplitude, averaging approximately 5 mm. Many of these stylolites disappear within a few centimeters with the amplitude decreasing laterally toward the pinch-out.

One of the most extensive and detailed studies on the stylolites in the Harrodsburg and Michel limestones in Indiana has been carried out by STOCKDALE (1922), who postulated that the stylolites are produced by the effect of pressures upon solutions and the differential solubility of limestone by utilizing Henry and Reicke's principles. The thickness of clay caps are dependent upon the purity of the limestone and the period during which the solution is actively dissolving material along crevices.

In a paper of summarization of his (STOCKDALE, 1922) work he (1923, p. 357) states that the length of the stylolites depends on the following three factors: (a) the length of time that the solution has gone on, (b) the solubility of the rocks, (c) whether or not the solution has attacked the ends of the stylolites.

He continues on page 358 that the variations in size, shape, distribution, and character of stylolites depend upon the following factors:

(a) the nature of the original crevice along which solution occured; (b) the composition and lithologic nature of the rock; (c) the erratic distribution of varying soluble portions of the rock; (d) the direction of pressure exerted upon; (e) the length of time solution continues.

Important evidences supporting his solution-pressure theory, according to him, are as follows (p. 262-264):

(1) the laminae of stylolites are sharply cut off at the edges of each column, (2) a slight sagging of stylolite seams, equivalent to the amount of penetration of the columns, is occasionally observed, (3) stylolites have the exact lithologic characteristics and color of the stratum from which they protrude, (4) fossils, oolitic grains, and mineral crystals are sharply cut off, (5) adjacent, parallel stylolite-seams often partially penetrate one another, (6) some traverse stylolites are observed, (7) the side-surfaces of stylolites are always striated.

In an upper portion of the Boone formation at Carthage, Missouri, BASTIN (1933) noted relationships between chert nodules and stylolites where stylolites terminate abruptly on the sides of the nodules. He considered both the cherts and the stylolites as having a secondary origin. According to his interpretation (p. 371, 377), regarding the time relationships between cherts and stylolites, the chert is a replacement of wall rock after the development of stylolite.

The chert nodules and stylolite relationship in Burlington limestone near Columbia, Missouri have been discussed by TREFETHEN (1947). In this case, the stylolites pass over the convex, upper surface of the nodule. According to TREFETHEN (1947, p. 58)," ... stylolites are diagenetic features, developed earlier in the history of consolidation than has generally been thought by advocates of the solution-pressure theory of stylolite origin. The stylolitic margins of many syngenetic chert lenses (with V-shaped openings or cracks) suggest a relatively early origin."

PRICE (1934) observed two types of stylolites in the White Media sandstone of Maysville, West Virginia, which occur along fracture lines, and along lower surfaces of quartz pebbles ("Gerolleindrucke"). He considered the stylolites to have developed by differential solution.

CAYEUX (1935), emphasizing micrographic analysis to solve the genetic problem of cone-in-cone and stylolitic structures, discussed some examples in France and believed that stylolites are developed by a pressure and dissolution phenomena without differential solubility-conditions along the stylolitic horizon.

STOCKDALE (1936) reports stylolites of the type 5 variety with amplitudes of about 1/4 - 1/2 inch. These occur in the Permian beds at West Amarillo Creek, Porter County, Texas.

SHAUB (1939) contradicts the solution-pressure theory with various objections as to the evidence and interpretations of STOCKDALE (1922, 1923, 1926, 1936, 1937). SHAUB regards the stylolitic structures in carbonate rocks as having an origin similar to cone-in-cone structures. For his ideas on cone-in-cone structures, see SHAUB (1937).

SHAUB (1939) mainly objected to differential solubility along the crevices or bedding plane as postulated by STOCKDALE. SHAUB (1939, p. 50) states the following: "It is difficult to conceive of any physical or chemical conditions which would repeatedly re-establish such a set of differential pressures in solid materials having the physical properties of a consolidated limestone, dolomite, marble, sandstone, or quartzite." As a solution to the problem of stylolitic genesis, he suggests that definite quantitative data on the fine grained sediments during the period of diagenesis should be considered.

The origin of stylolites according to the contraction-pressure theory postulated by SHAUB (1939, p. 53-54) is as follows:

> (1) During the process of compaction (of sediments) the interbedded clay bands become less permeable to water than the lime oozes and offer an increased resistance or retarding action to the upward movement of pore water.
> (2) The retaining action of the clay causes the pore water to accumulate in the lime ooze beneath the clay partings, thus keeping it in a more highly plastic condition.
> (3) The lime layer immediately above a clay layer or parting will become less porous and plastic, with increasing volume contraction as the pore water moves upward to the underside of a higher clay layer that is relatively more impervious.
> (4) The removal of pore water causes the lime particles to draw together laterally as well as vertically. The lateral contraction produces horizontal tensile stresses which are probably not very high .... . The greater the volume contraction, the greater the differential stresses may become.
> (5) The differential plasticities above and below the clay partings establish conditions where the more plastic material will flow into the places where the pressure is reduced. The process of compaction is under gravitational control, hence the normal direction of the transfer of material by plastic flow will be approximately at right angles to the bedding.
> (6) At the beginning of the plastic flow from one side of a clay band to the other, the clay is sheared and carried ahead of the penetrating plastic material. This motion between the parts on the opposite sides of the clay band is relative, slow, and usual non-turbulent.
> (7) The gradual removal of pore-water, and consequent gradual and continued volume contraction provide the necessary differential stresses for a prolonged transfer of the material, which will continue until the stresses become too low to overcome the resistance to plastic flow.

(8) Any thin bed which retards the movement of pore-water which comes in contact with the stylolite seams developed along crevices and faults may supply in colloidal form all the visible clay observed in such instances.
(9) Stylolites in sandstones and in quartzites are believed to originate in the same manner and for the same reasons as outlined above for their origin in lime oozes.

The evidences presented by SHAUB are: (1) fossils in the stylolitic column, (2) striations along the sides of stylolitic columns, (3) laminations in the limestone bent at the beginning of up-peak of the stylolite, (4) adhesion ridges.

He explains that the pierced fossils in stylolitic columns were already broken at the time of deposition or before the development of stylolites; the fossils are more easily broken or corroded because of their softness and holes. On page 57, he describes an irregular stylolitic column from the Lockport dolomite, New York showing striations converged downward which could not be produced in hard rock, as the result of relative movement due to the solution and static force of the overlying material. These converging striations are explained by GOLDMAN (1940) as some adjustment, between more rapidly and less rapidly advancing (dissolving) parts, which might take place by flow in the consolidated rock. On page 59, Figures 6 and 8, he notes striations on the side of a stylolitic column (specimen from Erie canal at Lockport, New York) which are crossed by wavy and traverse ridges believed to be due to adhesion between the column and the wall during the continued volume contraction after the column had pierced the adjoining unconsolidated plastic material.

"Drucksuturen" type of stylolites between rounded limestone pebbles in Potomac marble (Newark group of Upper Triassic age) in Maryland has been reported by BASTIN (1940).

Discussing the origin of stylolites, STOCKDALE (1943, p. 6) raises a question: "Is one to believe that the superabundant and sharply defined stylolite-seams of marble beds were spared the ravages of nature and survived the destructive processes of metamorphism which transformed the original properties of the rock?"

According to observations by the present author on stylolites in marble at the Administration Building of Missouri School of Mines and Metallurgy, cases are numerous where two or three seams spread out from a single seam. The direction of spreading is almost parallel to the foliation of marble. There are bases in which tails of stylolitic seams are bent. These bendings could be understood either as primary or as change of foliation lines locally during the metamorphism where this change did not affect the stylolitic seams compared to lamination of limestone itself. There are no reasons why the stylolitic seams must be destroyed during metamorphism.

STOCKDALE (1943) discusses stylolites along faults near the Douglas Dam, Sevier County, Tennessee. According to him, fault surfaces may offer easy access to percolating ground water which is the agent of solution in the stylolite-making process.

Stylolitic seams (type 5, with amplitudes from microscopic size to 1/4 inch) from a drill core sharply demarcated by thin films of coal are described by STOCKDALE (1945). In this case, the coal and stylolitic seams are inclined about 25 degrees to the local bedding plane. Such a portion as drill core of about 2 inches diameter could represent only local inclination. The present author has seen many cases of such inclination as much as 25 degrees at portions along horizontal seams.

SLOSS and FERAY (1948) report microstylolites in the Lower Cretaceous sandstone from Cut Bank oil field, Glacier County, Montana where the development of microstylolites and the consequent depositions of secondary quartz have reduced the primary porosity and permeability of the sandstone. It may be possible that some of the stylolites are not true stylolites.

Stylolites almost normal to the bedding plane in various limestone beds along the eastern flank of the Front Range and Wet Mountains of Colorado are reported by BLAKE and ROY (1949). In this case, stylolites as secondary origin, according to the authors, are due to orogenic pressure rather than static pressure. They describe a series of styloliitic seams almost normal to several shale layers. It would be interesting to see those shale layers, particularly at the portions where stylolite seams have been cut or suspended not to be developed because of the insoluble shales and also particularly along the layers between shale and limestone, whether and how much these shale layers have been subjected by the solution activities.

CONYBEARE (1949) describes a microstylolitic seam observed in thin-section from the Pre-Cambrian Saskatchewan quartzite where a quartz veinlet has been displaced by a stylolitic seam of low amplitude.

BASTIN (1951) describes a stylolite which has cut oolitic grains and from which he supports the stylolite genesis as secondary origin.

A subaqueous solution origin of stylolites in limestone has been proposed by PROKOPOVICH (1952), after he observed the stylolites occurring in the Muschelkalk and Malm limestone in southwest Germany. According to his proposal, many of the seams were developed on the sea floor and were, therefore, parallel to the bedding, but solution could also take place below the sea floor in the mud.

BERGENBACK and TERRIERE (1953, p. 1022) describe stylolite occurrance in Scurry Reef, Scurry County, Texas, stating "Many contacts between adjoining fragments (maximum diameter 5 m) in the calcarudite are stylolitic, but most stylolites do not continue into the matrix. This discontinuity indicates that the stylolites developed between the fragments, presumably by pressure-solution, before the matrix lithified."

Extensive study has been carried out by HEAID (1955) on the relationship between stylolites and the reduction of pore spaces in sandstones. He describes many styloltic seams developed between the grains of heavy minerals in sandstone. According to him, there is no proportional relationship between the amount of stylolites and cementing materials within a local area. Some of the stylolitic seams of microscopic size have developed after the initiation of authigenesis.

THOMSON (1959) studied on the Lower Silurian Green Pond Conglomerate in New Jersey. He concluded that development of pressure solution in sandstone is related to the secondary quartz precipitated along the original sand grains, and also related to the elimination of pore spaces due to this secondary quartz at the area of low pH and pressure. According to him, the development of the geometry of stylolitic structure between the quartz grains is the function of clay content and its composition between grains, grain orientation, and pressure exerted. The pressure-solution sutures studied by him are not related to regional metamorphism and depth of burial. Differential thermo-analyses of stylolitic clay indicate its composition as illite. The mechanism proposed by THOMSON to produce sutured structures between sand grains is as follows: Clay between grains is thought to be illite. Solution migrating through the sediments commonly is charged with CO_2 and various cations capable of replacing by cation such as Ca^+ of Mg^+. Base exchange of K^+ in illite by Ca^+ or Mg^+ leads to the formation of K_2CO_3, a strong alkali. In this way a zone of high pH is developed near the clay-rich area. The solubility of quartz increases directly as increasing pH value of solutions. Also increasing pressure tends to increase the solubility. As the result of dissolution of silica from the quartz grains, pressure-solution sutures have been developed. The dissolved silica will be precipitated at a region of low pH and pressure as secondary quartz, thus eliminating pore spaces in sandstone.

In regard to the elimination of pore-spaces in sandstone by the stylolite solution, HEAID (1959) states that the solution is localized by the material in clay partings rather than by freer circulation along bedding planes. On 251, he writes: "if circulation had been the controlling factor, solution would have taken place at grain contacts throughout the permeable beds rather than along definite seams." He continues, stating that quartz overgrowths are euhedral at the stylolite seams eliminating pore spaces during the last stages of stylolitic solution, while the rock was little indurated. In regard to the time of stylolite formation, he notes on p. 253 that many writers have claimed that stylolites post-date induration; however, stylolites may start to form relatively early and actually be an important factor in promoting induration. HEAID's paper (1959) may be summarized as follows: (1) solution must have been promoted by original clay or by the constituents associated with clay. Potassium from clay might be the promoting agent of solution (THOMSON, 1959); (2) the size of the seam would be related to the original amount of the constituent which causes solution; (3) stress required for pressure solution may not be as great as formerly believed; and (4) the lack of stylolites along a clay parting may be due to insufficient pressure, low temperature, or unfavorable clay composition.

BROWN (1959) reports stylolites from the Lower Carboniferous limestone in North Wales, with a marked concentration of quartz crystals at the stylolitic apices. From petrofabric study of these quartz crystals he found that the c-axes of the authigenic quartz crystals are aligned parallel to subparallel to the stylolitic "limbs" of the stylolitic columns and the apices of the stylolitic columns display a different orientation parallel in that the authigenic quartz crystals develop at right angles to those along the "limbs", and in the plane of the apex, whereas the quartz crystals in the matrix of the limestone show no referred orientation. From the examination made, he draws the following three conclusions on p. 255-258;"(1) in order that the authigenic quartz crystals might develop, there must have been solution and crystallization along the line of the stylolite; (2) to establish a marked orientation of the [0001] axes of quartz, some directive force must have been operative during the growth of the crystals; and (3) the stylolite developed after induration of the host rock since the authigenic quartz crystals represent post-induration phenomena."

The third conclusion of BROWN is not supported by evidence. There is no reason why authigenic euhedral quartz crystals should not form at any time of the induration process. According to SIEVER (1959, p. 65 and 69), secondary quartz overgrowths commonly show euhedral outlines only in the slightly or moderately cemented sandstones. In the extensively or completely quartz cemented sandstones the overgrowths have interfered with each other to such an extent that few euhedral faces are left. This may be true for the quartz in any rock, also in the oolitic limestones. Where there is more space for crystal growth, euhedral crystals usually form more readily.

ILLING (1959, p. 30 and 33) reports that well sorted and packed, bioclastic "orthodox" oolitic grains of upper Sunda formation in western Canada, show mutual micro-stylolitic grain boundaries before the remaining pore space was filled with clear secondary calcite. Also, crinoid ossicles and blastoid spines and plates were pressed into each other developing mutual pressure-solution (sutured contacts) during compaction.

GOLDING (1959) reports that in sandstone quartz welding results from concurrent stylolitization and silica cementation of quartz while clay compaction is continuing by load stress and is accompanied by illite authigenesis.

That stylolite forming processes produce pore-filling especially in sandstone has been mentioned by von ENGELHARDT (1960, p. 26).

Microstylolites in volcanic rocks are reported by BLOSS (1954) and GOLDING and CONOLLY (1960, 1962).

BLOSS (1954) reports microstylolites in brecciated rhyolite porphyry from the Burin Peninsula, Newfoundland. In this case, the spherulites and phenocrysts of both quartz and feldspar are removed by solution. Iron oxides disseminated in the matrix of the rhyolite porphyry consequently accumulate as insoluble residue.

GOLDING and CONOLLY (1960) report microstylolites in rhyolite from Goobang Creek, northeast of Parkes, New South Wales, Australia. In this case, stylolitic seams which consist of illite, serucite or sphene and leucoxene sometimes cut across the fluidal banding in the cryptofelsitic ground mass. In some cases, stylolites traverse quartz phenocrysts, presumed to be controlled by cracks formed during the inversion of high quartz to low quartz. In addition to traverse stylolites, distinctive lithologic variation within flow banding has been marked by stylolitic line (GOLDING and CONOLLY, 1962).

A stylolitic structure in an asbestos vein has been reported by MALES and GOLDING (1961). According to GOLDING (personal communication to G. C. AMSTUTZ, 1961), as a tentative interpretation, this stylolite-like seam is not due to the pressure solution but is probably due to the differential crystallization of fibres in an empty (or fluid-filled) cavity from the walls of this cavity towards the center. He notes that stylolitic structures may be more frequent in felsitic types than other igneous types.

C. A definition of stylolites

It is suggested here that in regard to the relationship of stylolites to individual rock grains, a classification of stylolites into (a) aggregate stylolites and (b) intergranular stylolites appears to be practical.

(a) Aggregate stylolites

<u>The lower limit:</u> Any departure of a bedding seam, usually marked by a layer of dark material, could be called a stylolite feature, if it fulfills the following conditions:

$$(1) \qquad S_v > D_{gr}$$

or, the height of the amplitudes, S_v (see Figure 37) has to be greater than the grain size, D_{gr}, of the material above and below the stylolite.

$$(2) \qquad S_v > S_h$$

or, the height of the amplitudes (see Figure 37) also has to be greater than the width of the individual (complete) units, whereby the true "unit" is defined as one "peak" or one "valley", or the portion circumscribed by the stylolite surface between two passages through the zero line (the average horizon line) as drawn in Figure 37.

<u>The upper limit:</u> The upper size limit of stylolites is harder to draw, because there is no actual upper space unit as was encountered on the lower limit. Therefore, the upper limit is more one of custom or terminology. There are large stylolitic features which by some are already included in the terminology of microtectonics or tectonics. As a matter of fact, stylolitic "walls" often look like the walls of fault planes with their stria and grooves. Also, many explanations of stylolites imply microstylolitic movement, with or without solution phenomena.

(b) Intergranular stylolites

Occasionally, one may find reports on stylolitic seams with amplitudes smaller than the grains. These stylolites may be classed into inter- or intragranular stylolites.

STOCKDALE (1936), SHAUB (1939), BASTIN (1940), SLOSS (1948), THOMSON (1959) and others also described intergranular boundary lines which look similar to stylolitic suture lines.

The processes taking place at single intergranular boundaries are basically different from those taking place in an aggregate. At simple boundaries, the stress-strain relationships and also the solution relationship are a function of the two neighboring grains only. The crystallographic orientation of the grains as well as their angle and amount of contact will influence the resulting interlacing boundaries. In other words, the physical and chemical space units to be considered in evaluating the intergrowth features of two individual grains are the crystal lattices of these two grains.

In an aggregate, on the other hand, the space units are the grains as a whole or even clusters of grains, and the features of the stylolites will depend on the aggregate structure and texture and not really on the crystal structure of individual grains.

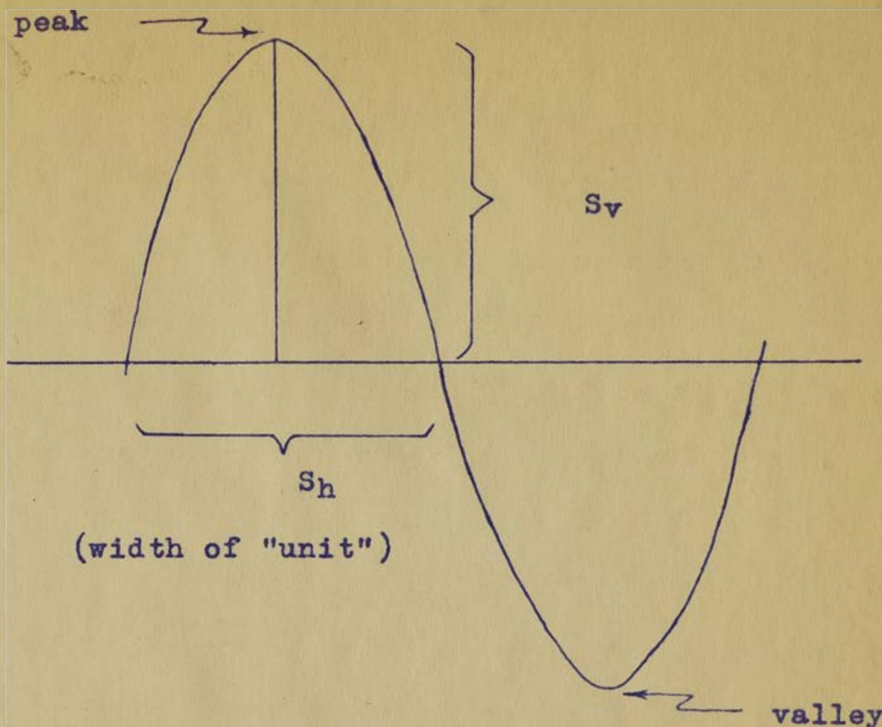


Fig. 37 . Definition of the basic elements and "units" of stylolites. ΔS_v may also be called amplitude in using a term of wave mechanics or optics, whereas 2 S_h can be called a period or "wave length".

D. Geometric classification of stylolites

In order to clarify any geologic phenomena, it is necessary to classify the facts or observations with regard to geometry, composition and, if possible, relative time of formation. Classifications are useful in order to approach a genetic solution and in order to differentiate clearly between observation and interpretation. The first classification of geological phenomena is a geometric one. Any first classification must be free from genetic interpretations.

An attempt has been made here to classify stylolites in the simplest and most frequently occurring patterns.

Some genetic connotations exist in the literature in regard to terminology of stylolites. This was, for example, the case of the terms "Drucksuturen" and "Stylolithen". The term "Drucksuturen" was used by ROTHPLETZ (1900), as mentioned above, for the lines developed between hard constituents such as pebbles or fossils. The term "Stylolithen" was applied to lines believed to have formed in a mud.

Six geometric types of stylolites have been differentiated as shown on Figure 38. This classification was originally based on observations in various stratigraphic horizons in limestones and dolomites of the Southern Illinois fluorspar district, in novaculite of Arkansas, and in the Pennsylvania Jefferson City limestone near Rolla, Missouri. Literature study has shown that it seems to be equally applicable to any stylolites reported from other areas. No other types of stylolites were found in published reports.

There may be gradational transitions between the various stylolite types included in this classification, often within one and the same stylolite seam. Observation has revealed that such transitions between type 3 and 4 occur frequently, even within 1 meter. Type 1 is often transitional, on one hand, to undisturbed, horizontal clay seams. It could be called, therefore, a high amplitude type of shale parting or shale groove. On the other hand, it may change, again within short distances, to type 2. This author, however, has not seen any transition between type 6 and any other types.

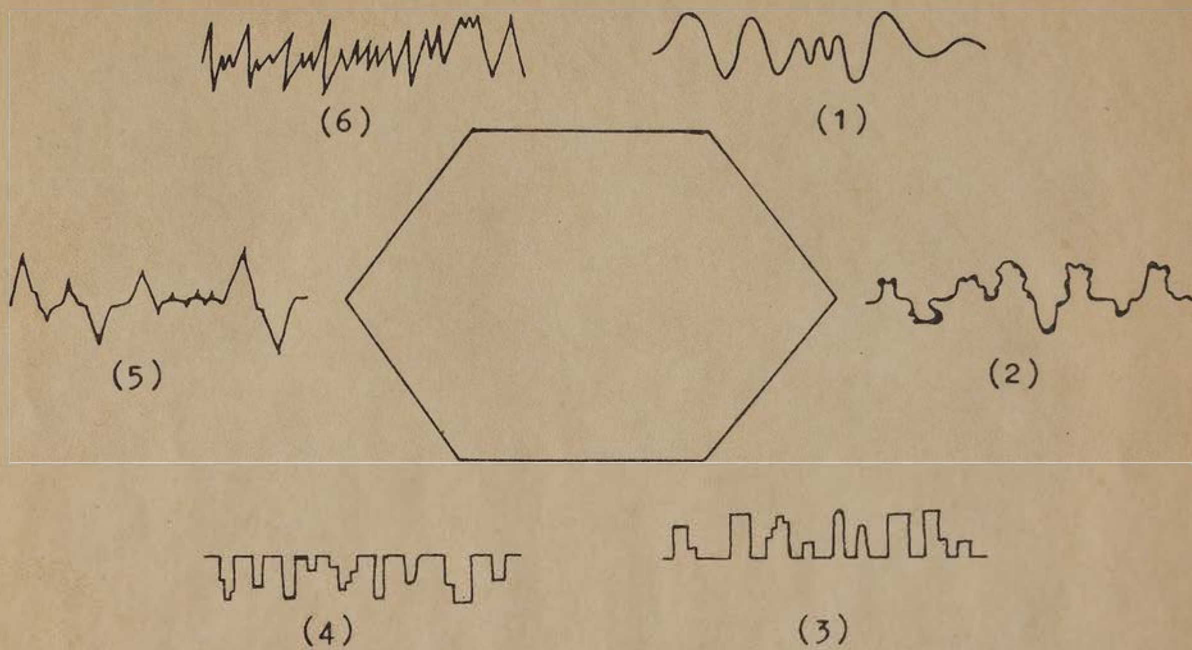
Type 2 (Sutured type, see Figures 39 and 40) is frequent in the Fredonia limestone in Southern Illinois and has relatively thick clay accumulations in the stylolitic crests and valleys.

Types 3 and 4 (Up-peak and down-peak type, see Figures 41 and 42) generally possess higher amplitudes compared to the other types.

Type 5 (Sharp peak type) possesses the lowest amplitude. Most transverse (inclined to bedding plane) stylolites are of this type. Transverse stylolites generally have small amplitudes with thin accumulations of clay.

Type 6 (Seismogram type, see Figures 43 and 44) is rare. It is found in the oolitic limestone of the Fredonia limestone in Hill mine of the Southern Illinois fluorspar district.

MEGASCOPIC GEOMETRIC CLASSIFICATION OF STYLOLITES



Type 1) Simple or primitive wave-like type

2) Sutured type

3) Up-peak type } rectangular type

4) Down-peak type } rectangular type

5) Sharp peak type (tapered and pointed)

6)"Seismogram" type

Fig. 38 . Classification is based only on the geometric patterns. Amplitude and thickness of seam material are not expressed, because they can change along the same seam. There are gradational transitions between all of the different types.

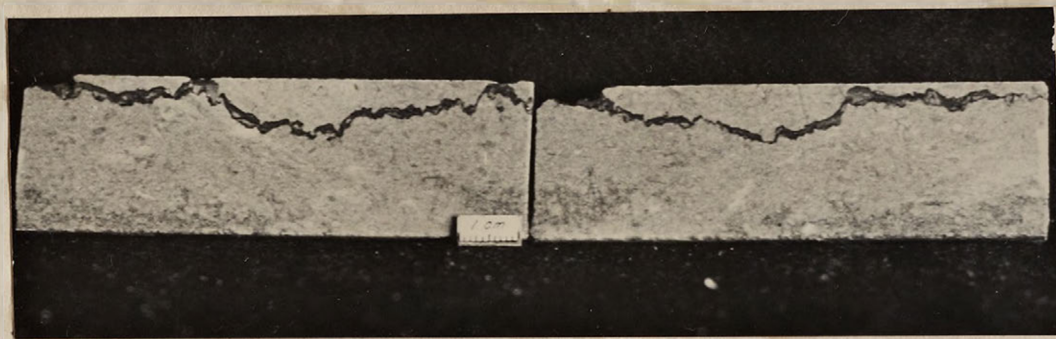


Fig. 39. Stylolite of type 2 variety. Drill core sampled at core storage, Hill mine, Southern Illinois. Top-bottom is not known.

Fig. 40. Stylolite of type 2 variety. Renault formation, Oxford mine, Southern Illinois. Note the small occluded sag penetrating down, upper right portion of the piece to the left.

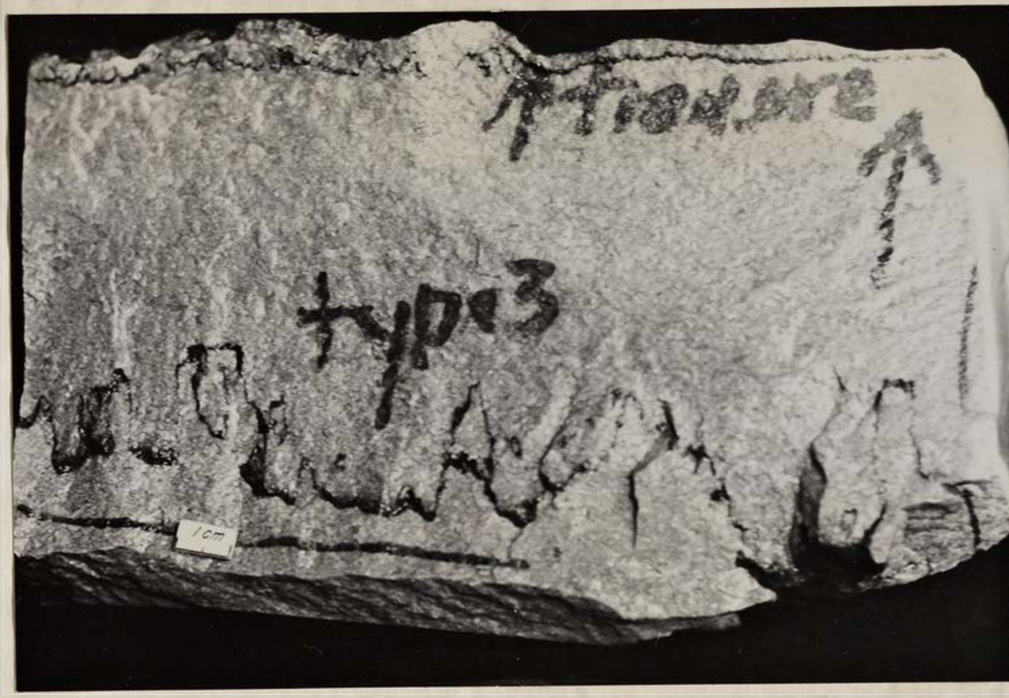


Fig. 41. Stylolite of type 3, up-peak type, from Fredonian limestone, Hill mine, Southern Illinois. Figure 34 is a section cutting this sample to the left.

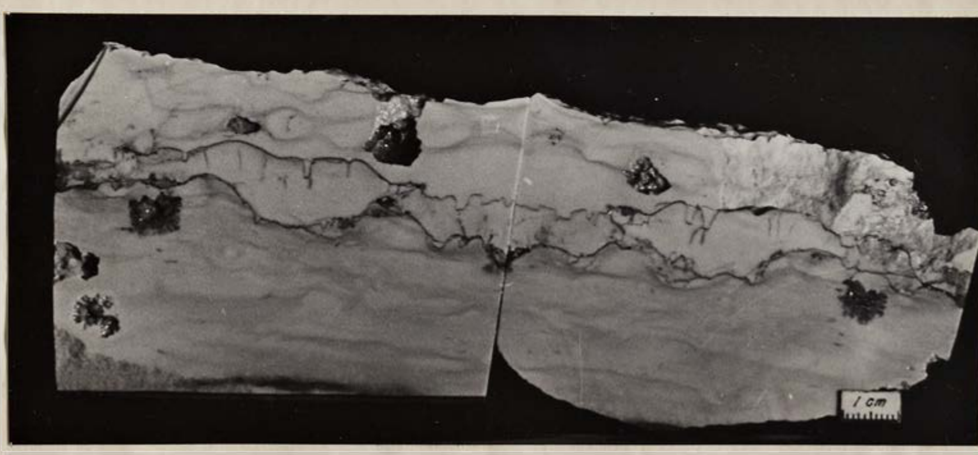


Fig. 42. Stylolites of type 4, down-peak typè, from Quarry Ledge limestone of the Jefferson City formation, 9 miles southwest of Rolla, Missouri. These styloltic seams contain fine grains of pyrite and marcasite. The spots are clusters and geodes of marcasite and quartz.

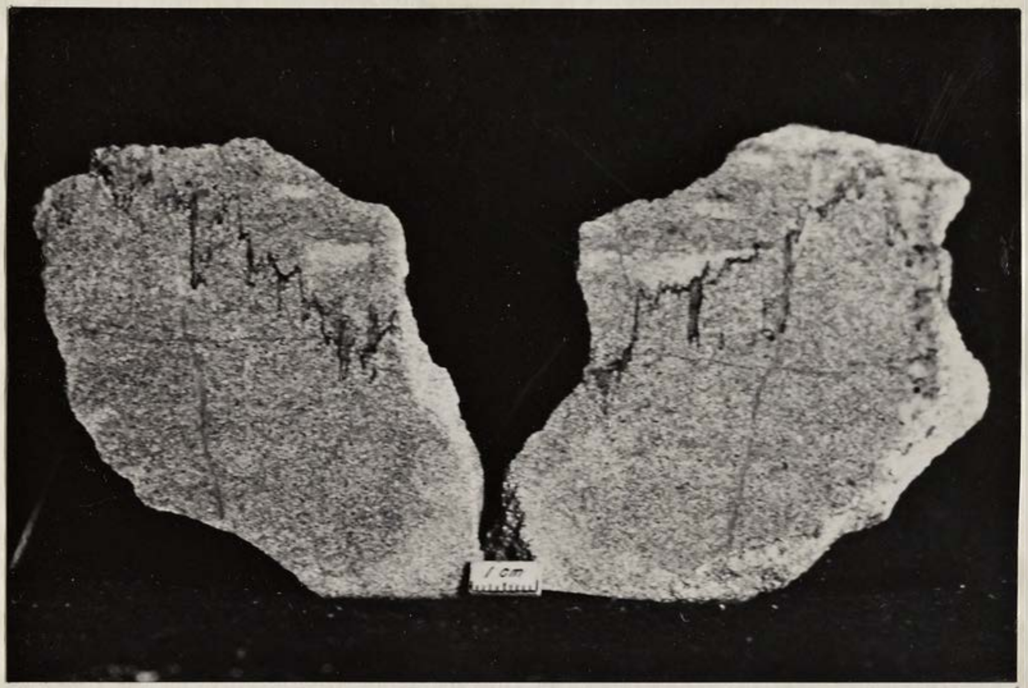


Fig. 43. Stylolite of a type transitional between 4 and 6, in Sub-Rosiclare oolitic limestone from Hill mine, Southern Illinois.

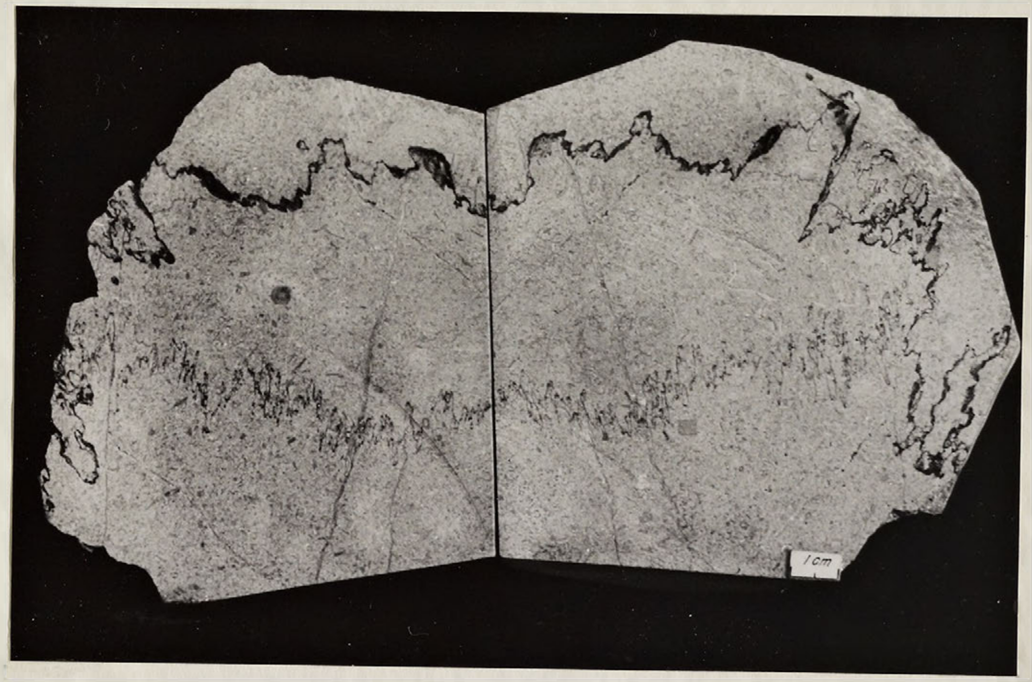


Fig. 44. The seismogram type has been cut by a big stylolite of type 2, sutured type. The big stylolitic seam consists of dark seam material and purple fluorite.

E. Relationships in space between stylolites, slumps, and banded ores

1. Upper Fredonian horizon (Hill mine)

General lithology: The Rosiclare Sandstone consists of 7 to 9 m of grey to green, fine grained sandstone. The lower horizon of this sandstone sometimes contains silty or shaly zones. Locally a dense greenish shale of about 25 to 70 cm occurs between the Rosiclare Sandstone and Fredonia Limestone. The upper 7 m of the Fredonia Limestone is a light grey to buff oolitic rock with a minor amount of dense dolomite. The regional dip of the strata in the Hill mine is less than 1 degree towards the N. N. W.

Abundant stylolites and fluorite were observed throughout the upper Fredonia limestone from the bottom of the Rosiclare sandstone down to 3 to 5 m below this contact.

Stylolites and related structures: Numerous horizontal seams of stylolites occur in the Hill mine. Some stylolitic seams are traceable more than 50 m along the clean walls of this mine.

Table II shows amplitudes and distances of some stylolitic seams. As shown on this table, the limestone lithology may or may not be the same below and above the stylolitic seams. Many seams change locally to shale partings or shale grooves. Thin stylolitic clay seams of small amplitudes are observed frequently between fluorite, calcite, and limestone layers. Also, normally, stylolitic seams seem to disappear gradually in the mine, because their amplitude decreases and the thickness of the "clay" gets thinner and gradually disappears when these seams pass into beds which contain coarse fluorite, barite and white carbonate. As will be shown in the microscopic section, the stylolitic seams do not actually disappear but take on the nature of typical stylolitic seams in coarse

Amplitude in centimeters	Type of limestone below and above stylolite	Distance traced in meters	Notes
1-2	A, B	10^+	Spreads into two seams
1-1.5	B, C	20^+	Disappears at baritic portion and continues on other side
variable	C, B	50^+	Changes twice to shale grooves (thickness 0.5 cm)
$1^{\pm}$	B, B	50^+	Disappears into slump shale
1.5	B, B	50^+	Spreads into two seams and continues
0.5-1	B, A	20^+	Changes to shale grooves
1.5	B, C	50^+	Changes once to shale grooves and is "disturbed" by fluorite, calcite and barite
0.5-1	B, B	10^+	Sometimes sharp boundary with coarse calcite or cut by calcite veinlet. Changes to shale parting at slump slope.
0.2^-	B, fluorite	1	stylolitic seam with very thin clay layer
0.2^-	B, fluorite	3	Changes to shaly parting of about 2 mm thickness
0.5	B, B	5	Disappears at portion of coarse fluorite and calcite
3-2.5	barite, A	0.5	See Figure 48a

Table II. List of the characteristics of a number of typical stylolite occurrences in the upper Fredonia limestone, Hill mine. A is buff dense dolomite, B is light grey oolitic limestone and C is light buff limestone.

grained material.

Displacements of a small stylolite, inclined about 80 degrees, by several horizontal stylolites occur at 70 m N. E. of the shaft of the Hill mine (Figure 45). The overall picture of this locality is shown on Figure 46; Figure 45 is a drawing of a detail in the last photograph to the right side of Figure 46.

Most of these displaced stylolites are type 5 (sharp peak type). As shown on Figure 45, one inclined microstylolite of type 5 has been displaced to the left about 2 or 3 cm. Two inclined microstylolites in the lower horizons demarcate barite veinlets and dolomite.

These dislocations of the inclined microstylolite could be interpreted in the following ways: The thin film of clay which marks the inclined en-echelon stylolite as also the barite in two layers, may have filled an inclined fracture. This was probably produced by means of an earthquake shock or by shocks produced by slumping movements occurring 1 m above, when the lime oozes were still in a plastic state. After this, pressure may have been exerted from the left to the right, displacing each consecutively higher bed along the several horizontal clay layers by a small amount.

The assumption that there has been movement is based on the observation of the rather regularly offset stylolite in the set of consecutive layers. This pressure may have been exerted from the left to the right by the weight of the beds themselves, pushing towards the empty channel at the right.

This almost vertical and very fine stylolite may have formed in two ways: (1) it may have formed by horizontal pressure similar to the way in which normal horizontal stylolites form by normal vertical pressure;

or (2) it may be merely due to the folding of the originally straight clay seam during compaction.

Probably, simultaneously with the horizontal pressure, stylolitic seams developed along the clay filled fracture. Also, vertical, differential, and static pressures due to the load of sediments may have produced the horizontal stylolites along the thin clay (?) seams.

To explain the offset of the inclined stylolite by means of solution activities, dissolving lime ooze near the horizontal stylolite does not seem to be possible in this case, because of the direction of displacement and inclination of this microstylolite. It seems logical that the time of displacement of the inclined stylolite and perhaps also the time of formation was earlier than that of the horizontal ones. The reason for this is simply the fact that the offsets themselves got involved in the stylolite forming process. This unusual feature may be related to submarine slumping occurring within 1 m above to the upper right of this en-echelon pattern.

A displacement pattern which has some similarity with the en-echelon pattern pictured on Figure 45 was described by CONYBEARE (1949). The main differences, however, are that the direction of offset is opposite, that he pictured only one displacement, and that the composition of the rock in his case is quartzite.

Another significant feature in the same locality, 70 m N. E. of the shaft of the Hill mine, is a channel of banded barite and fluorite, with an oblong cross-section 1 m below the slump to the right of Figure 46 and 1.5 m to the lower right of Figure 45. The thicknesses of the individual bands of barite and fluorite are less than 1 cm. Three or four sphalerite bands with small amounts of fluorite alternating with barite occur at the bottom of this channel. The amount of granular sphalerite mixed with fluorite decreases upwards. There are a few small, scattered crystals of galena within these sphalerite bands. Above 3 or 4 bands from the bottom, barite and dark fluorite bands alternate with one another, fluorite having taken over the "position" of sphalerite.

Under the microscope, the grains in the banded barite are oriented outward from the styloltic seam in a plumose pattern. Fluorite cuts vertically across this plumose pattern. Dispersed stylolitic "clay" does not occur between barite and fluorite. Portions of stylolitic seams are seen and seam material is scattered below and above the probable seams. The disconnected occurrence of the dense "clay" accumulations at stylolitic peaks is somewhat peculiar. Congruent to these seams, quartz crystals are scattered all along the seam, just generally in the true stylolitic seams. Also, xenomorphic or amoeba shaped sphalerite is scattered along the probable stylolitic seam.

A stylolitic "clay" seam demarcates the limestone from these bands along the upper contact on the left half of this structure. The amplitude of this stylolite decreases and changes to clay grooves along the upper right contact and the outside of this structure. The average thickness of these "clay" grooves is about 5 mm. Lenticular or augen-shaped dolomite lenses (length on the average of 2 - 10 mm) are enclosed in these "clay" grooves.

From the bottom contact of the upper limestone, stylolitic columns hang down like small stalactites from the roof of a vug which occurs at the opposite wall of this oblong channel. The portion directly below the stylolitic columns is empty. In this vug, horizontal layers of bitumen-stained limy sand with empty spaces in between the layers carry euhedral sphalerite, crystallized along the upper and lower margins of the tabular layers. It is not known whether the oblong baritic channel and this vug were connected or not, even though the two are connected by the same styolitic seam.

The contact at the bottom, between disseminated sphalerite bands (average thickness 2 mm) and the oolitic limestone, is styloitic. This styloitic seam is of very low amplitude and the "clay" layer is thin. Some oolites are pierced by this styloitic seam, as seen by the hand lens.

As shown on Figures 48a and b, there are two vertical calcite veinlets extending down from both ends of this channel. The thickness of these veinlets decreases downwards, towards the floor of the mine. Below and above the channel, neither oolitic limestone nor dolomite have been vertically displaced. Fracture-filled vertical fluorite veinlets above this channel are connected to the slump tail. As mentioned above, a slump structure occurs 1.5 m above this channel.

It is probably significant to the interpretation of this "channel" filled with banded ore minerals that a very similar although much smaller bended structure occurs 2 m to the upper left of the oblong channel (see the right side of Figure 46). This structure is again terminated to the left at a vertical calcite veinlet.

Perhaps the following interpretation best explains the formation of this channel: During the deposition of lime ooze, the two fractures on the bottom corners of the big channel and the fracture on the side of the small structure were developed by some sort of a shock. After this shock occurred, some of the soft muds may or may not have been eroded away leaving a slight depression. One barite layer was deposited in the low area and so on, with intermittent layers of fluorite. Because of the higher specific gravity of the barite (4.5) compared to the surrounding mud (specific gravity of calcite is 3 and mud is much less than that because sea bottom mud contains about 80% water at a maximum), we could expect a much more rapid rate of compaction below the barite than in the surrounding mud. Simultaneously with the compaction, more barite bands were deposited until the channel was filled and/or the barite source was depleted and the overlying mud deposited.

The banded feature may, consequently, be termed a rhythmite, in the sense of LOMBARD (1956). Rhythmites are not unusual. The only thing in this feature which is perhaps a little unusual is the composition, although barite and fluorite are really not uncommon materials. Therefore, the present feature can be perfectly well understood as a sedimentary rock. The search for an unusual interpretation must stem from some psychological prejudice (compare Figure 8) which may perhaps be caused by the rather "pretty" contrast of the barite-fluorite rhythmite.

A better understanding in regard to the formation of this channel would be provided when viewed in three dimensions. Figure 46 is actually a somewhat "cineramic" view and, therefore, offers aspects of the third dimension.

There are numerous additional variable features in regard to stylolites and related structures in the Hill mine. Some stylolites occurring close together may merge. Even in this case, the connecting "clay" shows stylolitic striations in contact with the host rock. This "three-dimensional" inter-connection is generally seen between the big stylolites.

Many times the author observed that stylolitic seams "degenerated" into "shaly" or "clayey" partings. It is hard to draw lines between stylolites and clay partings, especially at the transitional portion. The term "clay parting" is, here, used to define a certain grooved "clay" with seams in excess of 3 mm in thickness and which does not fulfill the definition of stylolites. Occurrences of partings where a transformation from a stylolitic seam to a clay parting takes place, are most frequent near the small "channels" which contain slumping evidence and brecciation. These channels are most abundant in the northeastern portion of the mine. The depth of these small slumping channels is between 50 - 100 cm. They contain broken shale with fluorite in the matrix. Six small slump channels were observed within a distance of 60 m along the mine wall. It is important to note here that these repeated slump channels are in a zone within 2 m below the bottom of the undisturbed horizontal Rosiclare sandstone. Because of the horizontality of the beds above and below these slumps, it is hard not to assume that these were formed prior to the deposition of the Rosiclare sandstone.

Stylolites may change to clayey partings either along the margins of the slopes of these slump channels, or anywhere within the rock but always parallel to the bedding plane. Some of these horizontal partings may split into two or three partings, meet again and subsequently be transformed again into stylolitic seams. In rare cases, the cross section of the rock mass embraced by two or more such parting and merging seams has not only the shape of long lenses, but even of almost circular masses. This can be observed at the northeastern portion of the Hill mine.

In many cases, the limestone surface in contact with a clayey parting shows slickensides; in other words, it is a horizontal slickolite. Also, many vertical calcite veinlets are displaced by stylolites; but some of the calcite veinlets cut them. The displacements of the calcite veinlets are variable, ranging from 2 cm down to displacements of microscopic scale. These displacements indicate that there were microslickolitic movements during early stylolitization. One of the displaced vertical calcite veinlets, under the microscope, shows well developed "micro-striations" parallel to the cleavage plane of calcite which may consist of pressure-twinning.

In some cases, stylolites terminate at clay partings, or stylolites merge into clay partings, as shown on Figure 49. The surface of the dolomitic (or limestone) nodule in this Figure, coated by a clayey parting, is grooved.

Massive sphalerite occurs **at** the valley of a stylolite as shown on Figure 50. Below and above this valley sphalerite grains are disseminated in the dolomite.

At or near the inclined surfaces of slumping slopes the stylolites generally "degenerate" into undulating or straight clay partings. This fact is illustrated in Figure 51.

Some stylolites with small amplitudes and thicknesses are cut or "invaded" by a stylolite of larger amplitude and thickness of clay.

At the Sub-Rosiclare horizon in the Hill mine, one vertical veinlet cut and partly destroyed a stylolitic seam (type 3 class, amplitude 4 cm maximum) as shown on Figure 52. Below the stylolite, fractures are filled with purple fluorite and calcite. The calcite veinlets are cut by later purple fluorite veinlets. As shown on this figure, a thin clay seam above the stylolite is conically centered on the vertical vein. Between this clay and the stylolite, the rock consists of a coarse crystalline dolomite and sphalerite grains are disseminated in it. Above this clay seam white and purple fluorite is present as impregnation. The veinlet is filled with dark coarse grained carbonate rock which has apparently moved down into the fracture. In this upper zone, sub-angular breccia pieces of 1 - 2 cm in average diameter are present. The breccia pieces look the same as the rock below the stylolite. They may have come from a nearby erosion surface and consist of the same rock as occurs below the stylolite. The upper outline of one breccia fragment was observed to be stylolitic, and the fragment completely enclosed with clay. The fluorite may have come up or gone down into the fractures.

2. Lower Fredonian Horizon (Deardorff mine)

General lithology: The lower Fredonian horizon is separated from the upper Fredonian by a zone of calcareous sandstone (sometimes referred to as the Sub-Rosiclare sandstone), 0-3 m thick in the Cave-in-Rock district. The sandstone is totally absent in the Deardorff mine except at the west end of the mine-working. In the Deardorff mine, dark brownish dolomite which overlies the calcareous sandstone (Sub-Rosiclare sandstone) is in contact with a grey to white oolitic limestone.

So-called "coon-tail" ores generally occur 0.5-1 m below the dark brownish limestone which is the base of the upper Fredonia limestone. The contact layer between underlying light oolitic limestone and the ore bands above are siliceous and have a dark color. This dark colorization might be due merely to an absorption effect of light by the microcrystalline quartz in this unit.

Stylolites and related structures: A few horizontal stylolitic seams occur in oolitic limestone below the ore zone and some "coon-tail" ores preserve stylolitic features between bands of fluorite and host rock. In this mine, the author could not observe any examples of transition of stylolites into clay partings and any examples of slumps like those in the Hill mine and the Oxford mine.

Stylolites occurring in this mine could be classified into the three following categories: (1) stylolites in grey oolitic limestone below ore bands, (2) stylolites in dark, siliceous carbonates transitional to (3) stylolitic features in the ore zones.

Stylolites between oolitic limestone and dark siliceous carbonate rock transitional to the "ore zone rock" are frequent (Figure 53), making concave or convex linear continuations. In one case a stylolitic seam between grey oolitic limestone below and dark transitional carbonate rock accurately follows at a definite distance of 4-4.5 cm below a sphalerite band for more than 15 m.

Many of the stylolitic seams between disseminated sphalerite zones and dark transitional carbonate rock have a lower content of the dark seam material and lower amplitudes than those occurring in grey oolitic limestone. Stylolitic features disappear megascopically in those cases where they penetrate into "ore zones." Examples are shown on Figures 26, 31, and 54.

3. Bethel and Renault horizon (Oxford mine).

General lithology: The Bethel formation is essentially a white to grey, well sorted, medium grained sandstone which contains minor amounts of shale partings. The base of the Bethel formation consists of 50-100 cm of greyish cross-bedded shaly sandstone.

The Renault formation essentially consists of grey to brownish crystalline limestone with an oolitic bed. Locally the upper horizon bears a chert bed of about 10 cm in thickness.

Some stylolitic seams are observed from the base of the Bethel formation down to 5-6 m below this base.

Stylolites and related structures: Because most of the mine walls are covered with clay material, it was not possible to find or observe stylolitic features and their related structures except in the areas where slumps and fresh walls are exposed. The clayey dust on the mine walls is due to the content of argillaceous material in the base of the Rosiclare formation. Several stylolitic seams below the base of the Rosiclare sandstone occur in crystalline carbonate and buff oolitic limestone.

Amplitudes of the stylolites are smaller in general than the stylolites occurring in the Hill mine. Stylolites in the Oxford mine are frequently of type 2 in the classification. No horizontal transition of stylolite into a clay parting was seen in this mine.

Many calcite veinlets are displaced by stylolitization (Figure 55). It seems that statistically the distance of displacement is proportional to the amplitude of the stylolite. There are only a few cases in which calcite veinlets are not displaced by stylolites.

Some stylolitic features of this mine related to sedimentary structures, such as slumping and compaction phenomena, will be discussed later under the sub-headings on the slump structures and the stylolites and compaction of sediments.

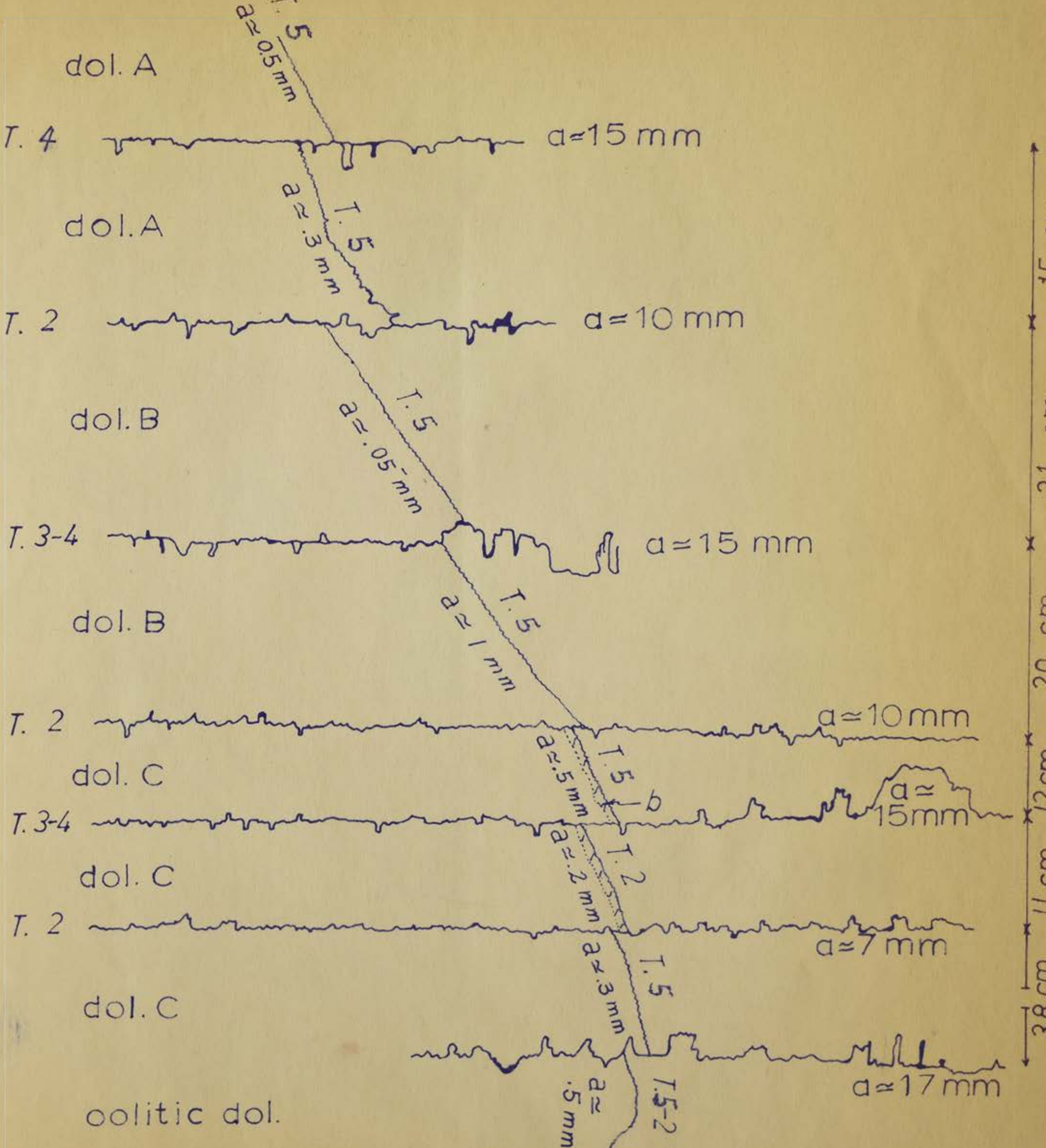


Fig. 45. "En echelon" of inclined microstylolite seams.
(1m to the left of barite-channel shown on fig. 48 a)
a : amplitude of stylolite , T : type classification, dol : dolomite
b : barite

Fig. 46. Panoramic view of a mine stope 70 m northeast of the shaft of the Hill mine, and just below the base of the Rosiclare sandstone formation. Dark lines and dark portions are shale. Note the slump structure on the right of the picture. Long bedded limestone lenses or layers occur within this slump structure and are interfingered with clay layers. Both may have undergone some redeposition or movement during the process of sedimentary slumping (see Figure 47). The en-echelon pattern of inclined microstylolites pictured in Figure 45 occurs at the right side of the picture, and the oblong barite channel pictured in Figure 48a occurs near the lower right side. The white horizontal bands are barite and calcite and the vertical veinlets are calcite. The distance from one end of the picture to the other end is about 5.5 m.

Fig. 47. Tongues of limestone and dolomite with shale occurring within the slump structure. The portion with the "20" mark is coarse crystalline dolomite. The finely laminated carbonaceous shale indicates flowage. Some of the shales have been crushed and this may indicate that it was in a rigid or a semi-consolidated state at the time of slumping. Note the stylolitic black lines between shale and carbonate rock lenses. The arrow indicates the top of the sample.

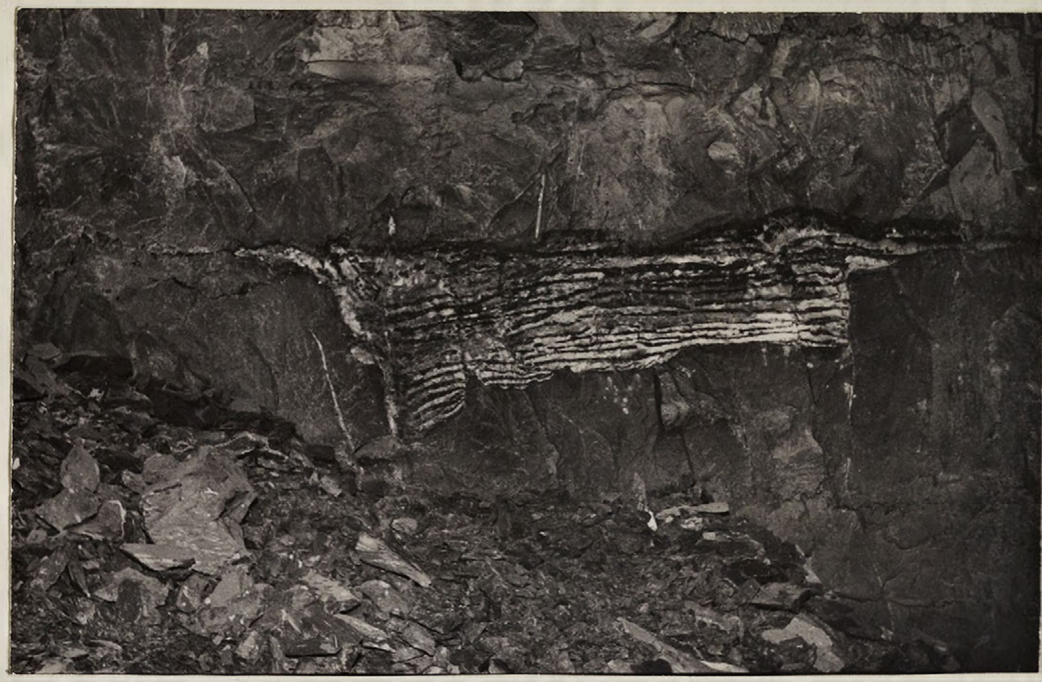


Fig. 48a. A channel filled with a barite (white)-fluorite (black) rhythmite. It occurs 70 m northeast of the shaft of the Hill mine. Figure 48b is a detail drawing of the left side of this channel. The scale is given by the pencil above the channel (length: 13 cm).

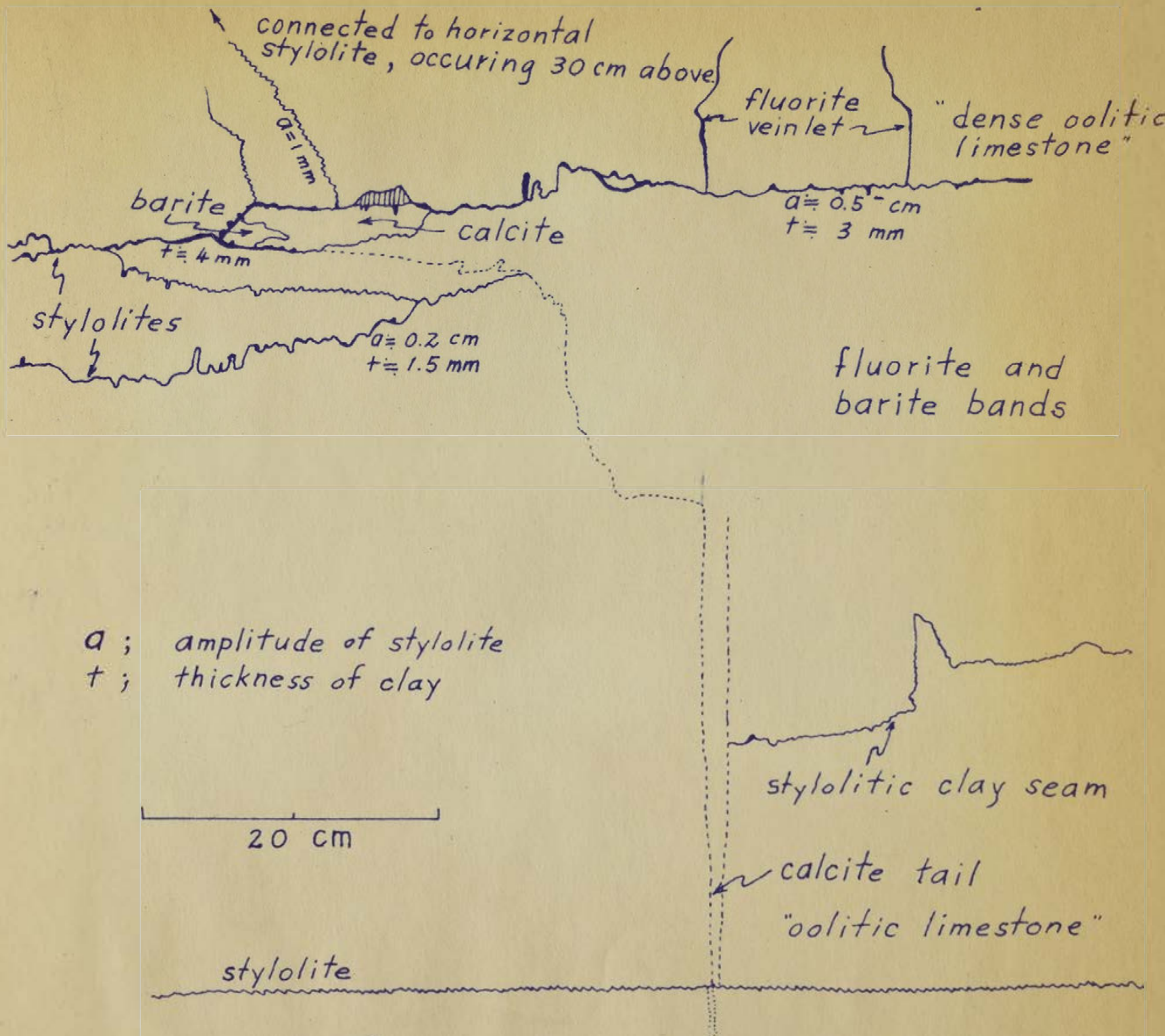


Fig. 48 b. Detail drawing of the left side of the oblong barite channel, Figure 48 a.

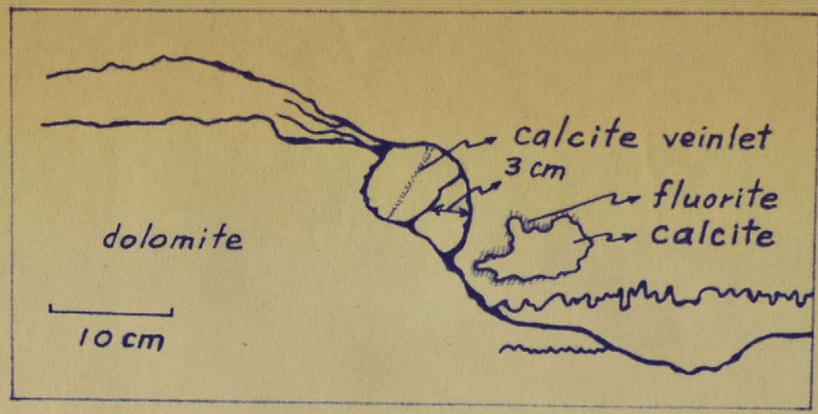


Fig. 49. Stylolite and clay partings.

Fig. 50. Massive sphalerite at the valley of a stylolite.

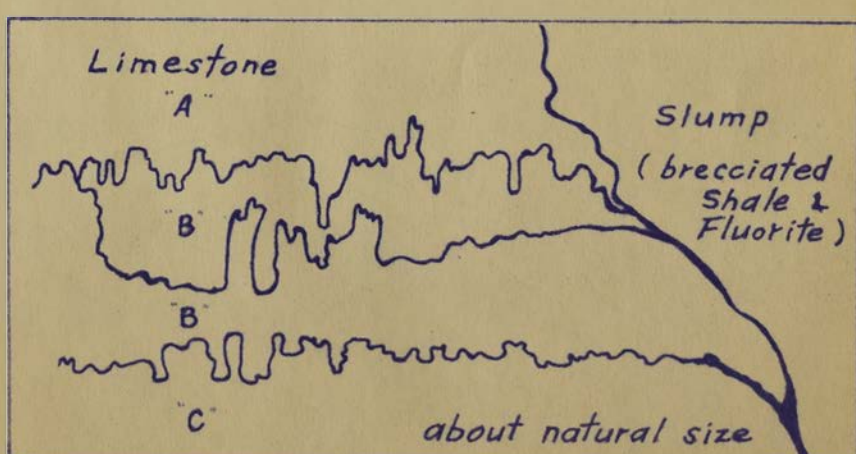


Fig. 51. Degeneration of stylolites into clay partings near the surfaces of slump-slope.

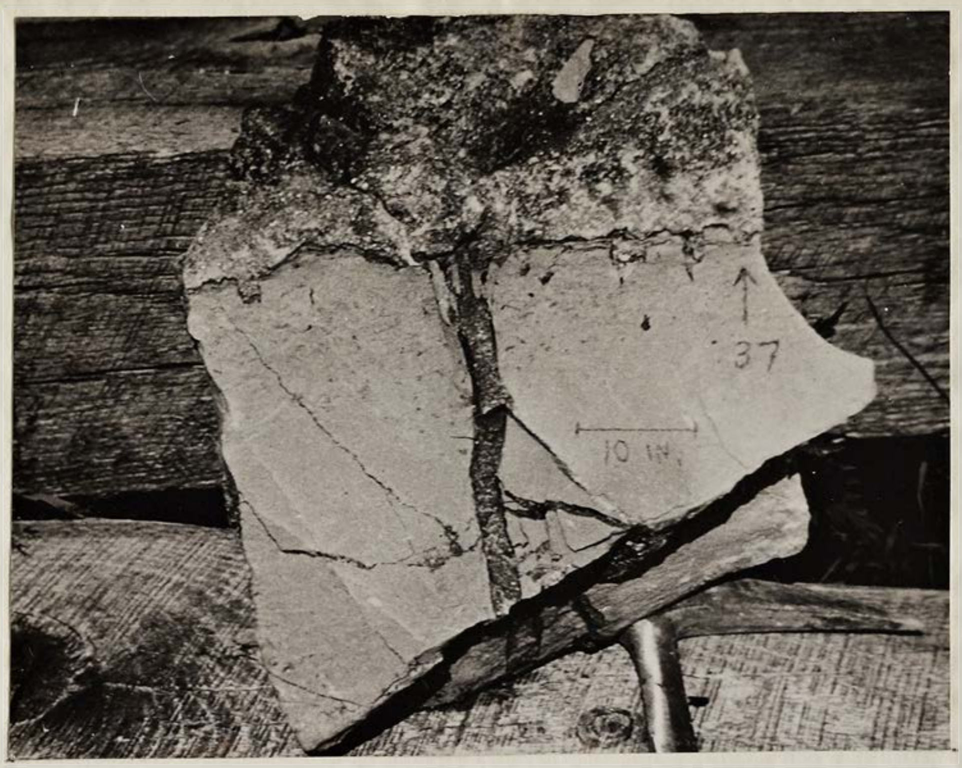


Fig. 52. Stylolite demarcates fluorite bed and limestone. Vertical vein cuts stylolite. Purple fluorite occurs alongside the vein walls and the fractures in the lower host rock. The vein is filled with dark coarse grained carbonate rock occurring above the stylolite. Also purple cubes of fluorite crystallized in small cavities; hexagonal quartz crystallized on these fluorite cubes. The vertical downpeak of the stylolite is about 4 cm maximum. The thickness of vein is about 1 cm and the scale on the picture is 5 cm instead of 10 in. Sample is from 3 m below Sub-Rosiclare sandstone and lower Fredonia limestone contact at the southwest end of the Hill mine.

Fig. 53. Type 3 stylolite between a light brownish oolitic limestone (below the stylolite) and a dark siliceous carbonate rock (above), 20 cm below a disseminated sphalerite zone. Lower Fredonia limestone, Deardorff mine.

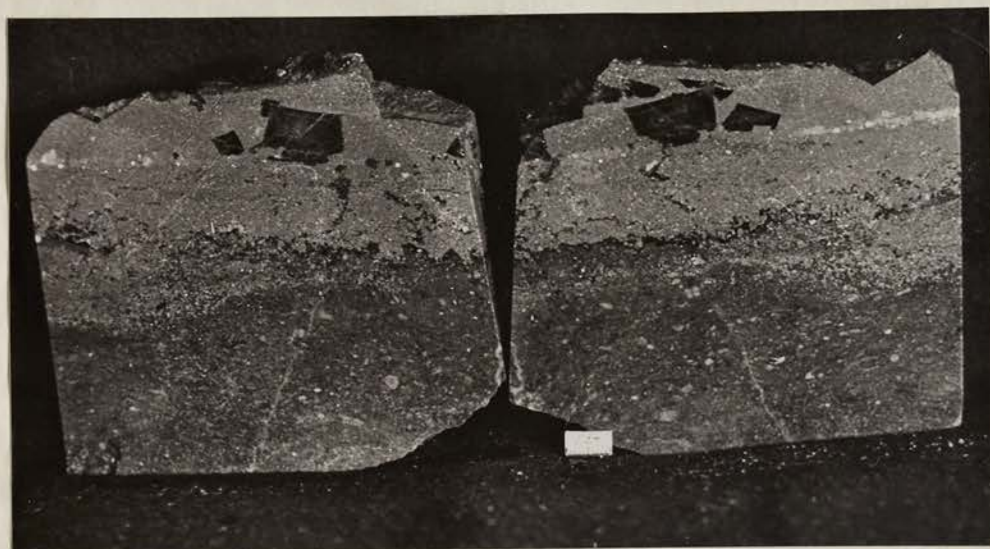


Fig. 54. A stylolite with a low amplitude between disseminated sphalerite zone (above) and dark siliceous carbonate rock (below); the stylolite seam gradually disappears (megascopically) as it passes into the disseminated sphalerite zone. The bright grey spotty band about 2 cm from the top of the specimen is galena, and the dark cubes are fluorite crystallized over the galena band.

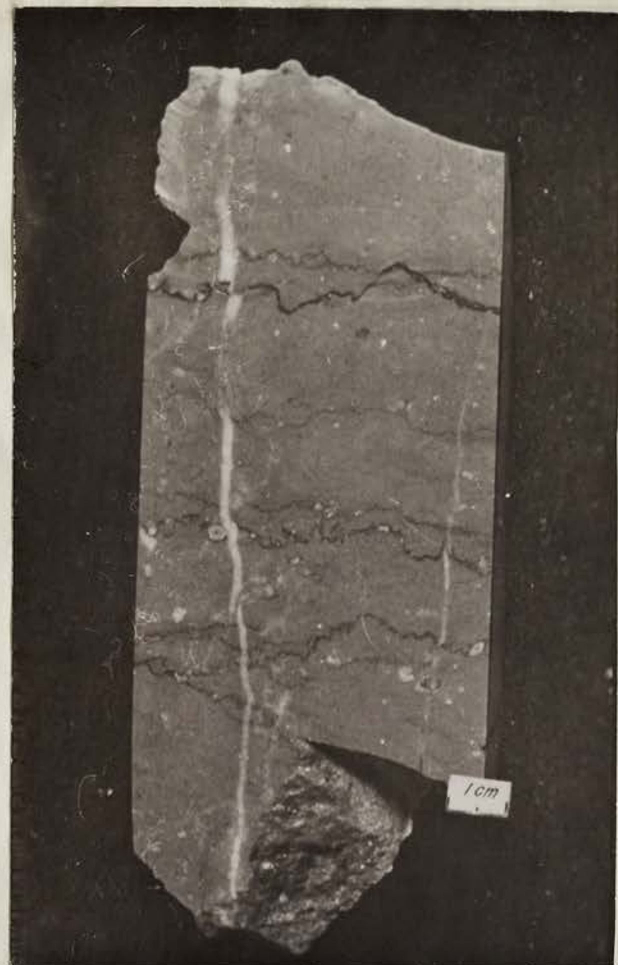


Fig. 55. Displacements of a calcite veinlet in a light massive limestone. A few oolites and fossils are enclosed in stylolitic valleys or crests. In the upper part of the picture, a type 2-1 stylolite joins and leaves again a smaller, grey stylolite seam. The sample is from the upper horizon of the Renault formation, southeast end of the Oxford mine.

4. Slump structures

a. Hill mine

Slump structures of variable size and mode occur below the base of the Rosiclare formation. The Hill mine workings were advanced along a longitudinal depressed valley recognized by the conditions of the base of the Rosiclare formation in Figure 10. Some parts of this depression contain numerous small slumps, which may have resulted from local erosion or faulting. Over these slump structures the base of the Rosiclare sandstone has locally collapsed after lithification. In many instances, accumulations of ore minerals occur in these slumping and collapsed structures.

According to the size, the slumping pattern, and the materials filling them, these structures could be categorized as follows:

(1) Sets of many slump structures filled by brecciated greenish shale below the base of the Rosiclare sandstone, their depth below the Rosiclare being less than 1 m.

(2) Large scale slumping channels filled with brecciated greenish shale and masses and veinlets of fluorite.

(3) Slumps filled with finely laminated black shale and sandstone (Rosiclare) resting on or submerged into the black shale.

(4) Slumps filled with finely laminated black shale (clay) with carbonate grains and boulders.

(5) Clastic shale dikes.

These five different types of slumping structures will now be discussed in detail:

(1) Complete sets of slump structures occur along the walls of the main haulage, to the east of the shaft. The term "sets" implies, in this case, an orderly succession and does not imply a time connotation. Also,

it implies that the slumps occur at a certain interval of space (distance) from one another and below a definite upper horizontal limit, i.e., the base of the Rosiclare sandstone. A similar feature is described by SHROCK (1948, p. 270). The interval between each slump structure varies from 10 to 15 m. They become somewhat larger towards the elliptical breccia channel, of which short and long axes respectively are about 30 and 120^+ m (see Figure 10).

Figure 56 is an example of one of these slump structures occurring in sets. In these slumps, brecciated greenish shale and sub-angular to longitudinal carbonate breccias are the filling material. Purple fluorite fills the spaces between the broken shale fragments. The slide slope shows slickensides which indicate downward movement, probably due to the load of the overburden. As shown in Figure 56, a small, almost vertical fault, also filled with black clay, has developed to the left of the structure. Many stylolitic seams and clay partings trend downward near the slump-slopes.

With regard to the time of formation of these slumps, the author thinks that it took place prior to the deposition of the base of the Rosiclare sandstone, because normally the base of the Rosiclare sandstone is not disrupted. Therefore, the formation might have taken place as follows: After the shale was deposited, turbulent flows cut channels into the beds of shale and the underlying mud. During the quieting of these turbulent flows the broken shale and mud filled into these eroded channels. At the time that the turbulent flows were present, the shale was enough compacted to react in a rigid way. Local elimination of this greenish shale in the Hill mine (see Figure 11) indicates that there were considerable amounts of shale eroded by these sub-aqueous currents.

(2) Large scale slump-channels, filled with brecciated greenish shale and fluorite as interstitial material between the broken shale fragments, occur at a few places near the northeast breccia channel of the Hill mine. Materials which fill these slump-channels are greenish shale and limestone breccias, with the size of the breccia fragments generally varying from about 5 to 10 cm in length, and also purple fluorite veinlets. All these materials are randomly oriented. Figure 57 is an example of this type of slump. The formation may be similar to but larger than that of the type (1) category described above.

(3) Figure 58 is an example of the third category of slump structures which occurs at the lowest working level, the northeast end of the Hill mine, where the central zone of the breccia channel is located.

In this case, fine laminae of clay occur along the slope of the upper Fredonian limestone and the broken semi-rectangular Rosiclare sandstone breccia fragments, which vary in size up to more than 1 m in diameter, have sunk down into the clay. On the upper right side of Figure 58, a piece of Rosiclare sandstone has sunk down vertically into hydroplastic mud, compressing the laminae vertically and showing a clear geopetal feature. Also to the left of the same figure, the crumpled and folded laminae indicate penecontemporaneous deformation, probably due to the subaquéous gliding down on an inclined slope. Similar geometric features are well described by SHROCK (1948, p. 153-170). Apparently, the Rosiclare sandstone was broken over these channels because the compaction still proceeded in the channel filled rich in water containing shales, and thus removed the support from the roofing sandstone. Thixotropic phenomena might have occurred at the beginning of the slumping of the clay.

(4) The fourth category, slumps filled with finely laminated black clay and carbonate grains and boulders occur near the collapse area, which

occurs about 150 m east of the shaft of the Hill mine. Figures 59 and 60 show portions of slump belonging to this category.

The slope of this slump dips 20 degrees towards the center of the "collapse area" and the length of this slope is traceable for about 30 m. Approaching the "collapse area", the intensity of the disturbance of both the upper Fredonian limestone and the Rosiclare sandstone increases. It is worthwhile to note here that no greenish shale occurs around the periphery of this "collapse zone", from which one may derive that this area has undergone a considerable degree of sub-aqueous erosion.

As shown on Figures 59 and 60, the clay laminae surrounding the limestone breccia fragments and grains show geopetal features. The shape of these limestone breccia fragments varies from sub-angular to lenticular and the size from 1 m up to less than 2 cm in average diameter. The size of the limestone grains varies from 2 mm to 1 cm in diameter as shown on Figure 60. Some of the grains are augen shaped. A few of these breccia pieces contain oolite-shaped fluorite. The layers of the clay laminae show shiny surfaces without concoidal fracture. This indicates that there occurred some downward movement after the deposition of this clay which must have had some degree of coherence.

It is known that sedimentary breccias produced by submarine sliding occur in the southeast Missouri lead district (SNYDER, 1957).

From the following facts:

— absence of greenish shale around the periphery of this slump structure,

— geopetal features, i.e., bending and arching of the clay laminae around the lenticular and semi-angular limestone fragments,

— limestone grains occur more intensely along certain layers,

— the Rosiclare sandstone above the slump is not disturbed,

— clay partings are bent and join together down the slump-slopes, we may conclude that this type of slumping took place under water. The breccias and grains of limestone were transported from elsewhere by subaqueous waves and then deposited.

The mechanism of slumping of muddy sediments is discussed by JONES (1944). According to him, (p. 152), "the breakdown of the structure of the mud takes place first at the shear surface, and results in a discharge of water which liquifies the mud near contact and also greatly lowers the resistance to shearing forces. For both reasons the material slides readily, as on a greased surface."

According to SUGDEN (1950, p. 35) submarine slumping can take place on slopes of very low angle, far less than the normal critical angle of rest in water of the sediments involved.

(5) Clastic dikes of sand, silt, clay, calcareous materials, gravels, coal and asphalt have been reported in the literature. A clastic shale dike shown on Figure 61 occurs below the undisturbed base of the Rosiclare sandstone.

According to SHROCK (1948, p. 212), there are two types of clastic dikes if genesis **is** considered: (1) those formed by intrusion of clastic or fluid material derived from some underlying source layer and emplaced under normal pressure and (2) those formed by introduction of material from above either under some pressure or by simple filling of a pre-existing crack or crevice.

The second type of clastic dike has been described by many authors; CROSS (1894), COLLINS (1925), NEWMAN (1903), JENKINS (1925), KRUGER (1938), and WILLIAMS (1927).

HULTZSCH (1959) described very similar geometric patterns of small dikes of clay in sandstones in the Quaternary of Germany.

Figure 62 is an important feature in regard to the tectonic movements during the formation of the upper Fredonian limestone and the time of stylolitization. Dolomite "A" is whitish dolomitic limestone with oolites and dolomite "B" is light brownish crystalline dolomite. Solid curved lines indicate clay lamination. By some sort of movement after the deposition of dolomite "A" and "B", there was a rearrangement and brecciation of certain layers and dolomite ooze "B" was penecontemporaneously filled into the spaces between the broken pieces. It is reasonable to assume that the stylolites on top of dolomite "A" were developed prior to the brecciation of "A". If the stylolitization would have been post brecciation, stylolites would likely have developed continuously into the dolomite "B".

Shale and dolomite breccias in carbonate rocks occurring in the southeast Missouri lead district were reported by SNYDER (1957, p. 906).

Greenish shale breccias (av. dia. 0.5 - 1 cm) in dolomite as also breccias of the Rosiclare sandstone have been observed at a few instances in this mine.

A sample of dolomite including shale breccia taken 50 cm to the left of the clastic shale dike of Figure 61 contains 60% of insoluble residues consisting of 80% clay and 10% each of quartz and fluorite by volume. An insoluble residue study has been carried out according to the method described by McCRACKEN (1949) at the Insoluble Residue Laboratory of the Missouri Geologic Survey and Water Resources in Rolla.

A thin section of the same sample shows the following mineral content: dolomite 50%, scattered clay 20%, quartz 20%, and fluorite 10%. Clay minerals are scattered through the whole rock and fluorite is filled as interstitial material between the euhedral dolomite crystals.

Figure 61 is an example of a clastic shale dike occurring 50 m east of the shaft of the Hill mine. Materials filling the crevices are tabular fragments of shale (length 2 - 5 cm) in a shaly matrix. The matrix in most of the dike does not consist of the carbonate rock surrounding the dike (to the end of the dashed lines on Figure 61, there is no carbonate matrix), but at the lower end of the dike, the matrix is the same as the adjoining carbonate rock. At the upper portion, fluorite also occurs between the shale fragments and sometimes it occurs in fractures within shale fragments. The wall of the funnel is somewhat curved at the end but there does not seem to be any deformation of carbonate rock near the contact with the channel. The downward motion of shale probably took place in a soft dolomite (?) ooze.

This interpretation is all the more probable in view of the evidence offered by a feature drawn on Figure 62. This is a drawing of brecciated dolomite imbedded in a different dolomite and some clay occurring only 20 cm to the left of the lower end of the shale dike. Apparently the dolomite layer occurring above the horizontal stylolitic seam (see Figure 61) was hydroplastic at the time of the formation of this clastic shale dike.

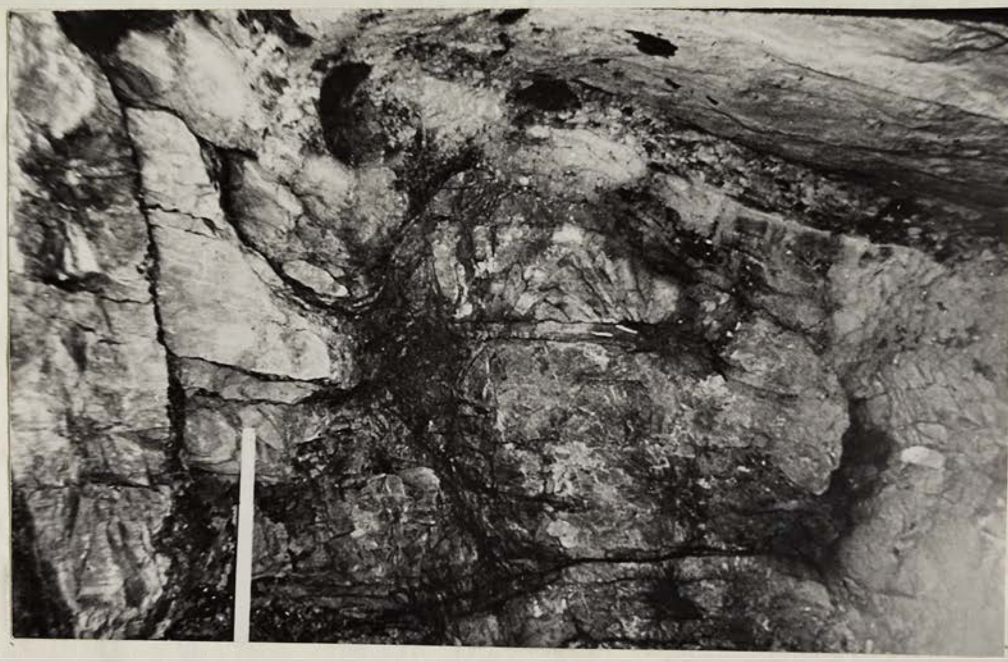


Fig. 56. An example of a slump structure belonging to the set of such structures occurring along the main haulage way to the east of the shaft of the Hill mine. Greenish shale occurs beneath the mine-roof which is the base of the Rosiclare sandstone.

Fig. 57. A slump channel occurring at the northeastern end of the Hill mine. The brecciated shale fragments have slid down into the channel. The layered breccia pieces to the left of a white strip of paper (scale = 12 cm) are composed of limestone. At the lower center portion of this slump, broken limestone is seen; the matrix is filled with carbonate material and purple fluorite. This brecciation is not readily visible in the photograph. The roof is composed of the slightly broken basal sandstone of the Rosiclare sandstone. Note the downward trend of the stylolitic seams near the slump surface. The limestone dips about 20 degrees away from the reader.

Fig. 58. Penecontemporaneous deformation of clay along a slump slope. Note a geopetal feature appearing on the upper right side of the picture: a rock fragment presses down shale laminae.

Fig. 59. Dark clay laminae enclosing grains and much larger pieces of limestone. The bending of clay laminae is probably due to the weight of the pieces of compacted limestone. Note that two clay partings crossing the hammer to the left, adjoin the clay layers along the slope surface. The picture was taken about 150 m east of the shaft of the Hill mine.

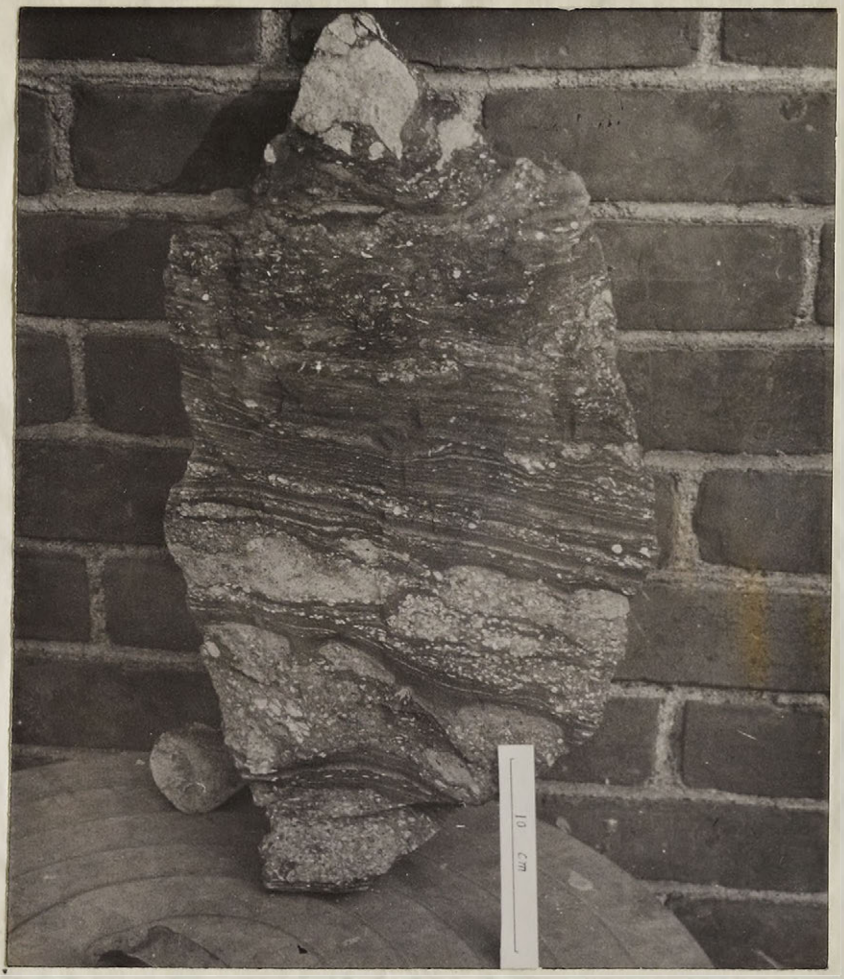


Fig. 60. A close-up picture of the rock type occurring at the area of Figure 59. Various geopetal features are seen.

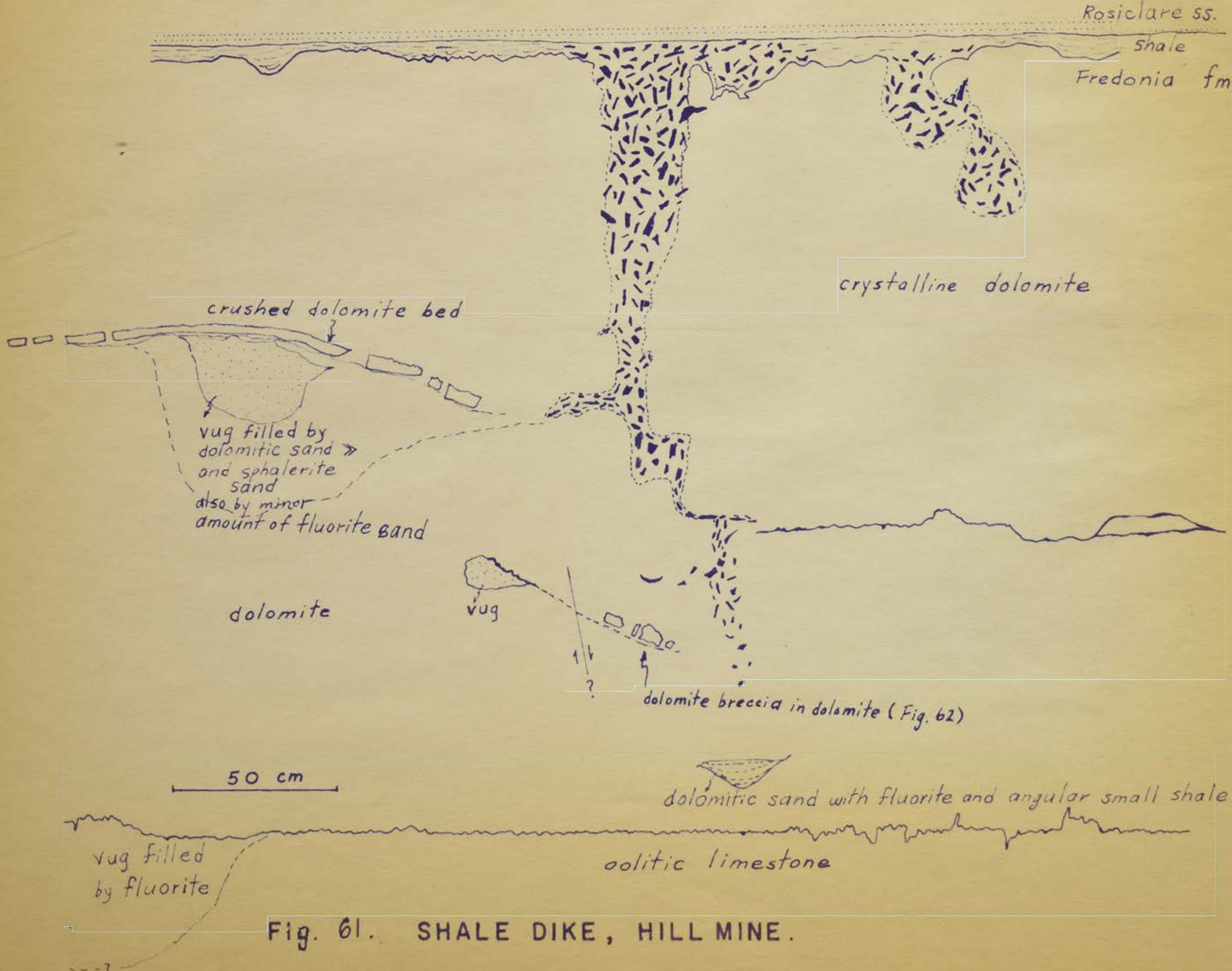
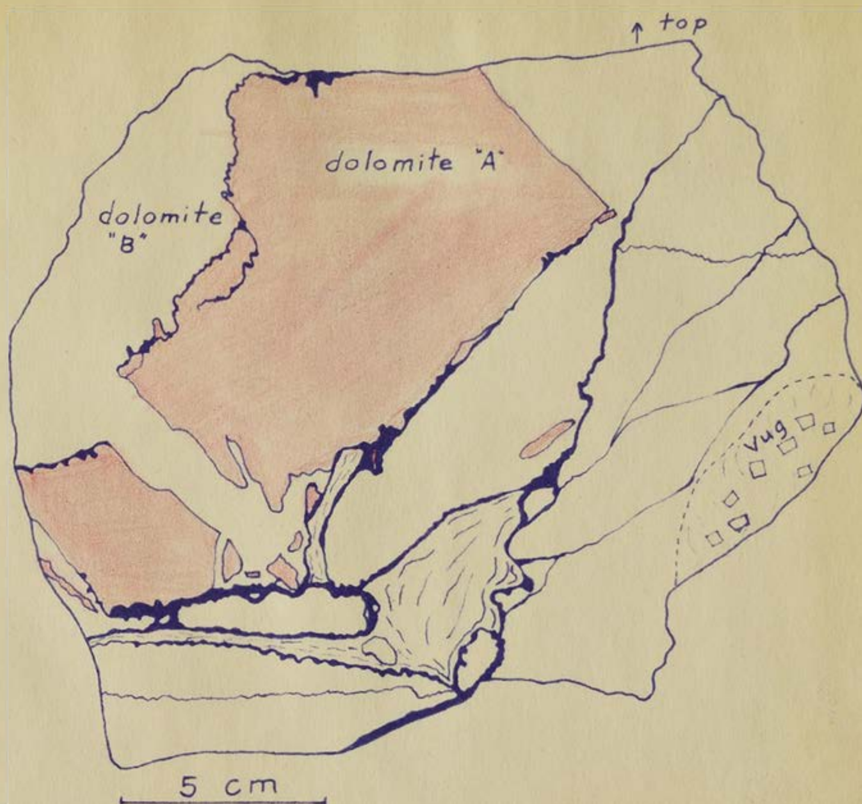


Fig. 61. SHALE DIKE, HILL MINE.



DOLOMITE A

DOLOMITE B

FLUORITE CUBE

CLAY SEAM

STYLOLITE

Fig. 62. REARRANGEMENT OF BRECCIATED DOLOMITE A. SEE FIG. 61, LOWER CENTER. HILL MINE, S. ILLINOIS FLUORSPAR DISTRICT.

b. Oxford mine

Not quite as many slump structures were observed in the Oxford mine. Three typical ones were selected and are here described. Figure 63 is a photograph of a slump structure shown in Figure 64, which is of a channel exposed in a pillar, 50 m south of the shaft, Oxford mine. Figure 65 is a detailed drawing of a square marked in Figure 64. Two more similar structures are exposed on the wall of the same pillar 10 meters to the right of the one shown on Figure 64.

As shown on Figures 64 and 65, stylolites are trending downward into the slump surface of the channel. In general, each stylolitic seam becomes thicker and the amplitude decreases near the slump surface. The relation between thickness and amplitude of the stylolites numbered on Figure 64 are shown on graphs 1 and 2. Several of the steeply inclined stylolites display a wave-like pattern near or along the slump surface.

The dolomite "horse" in the clayey soft carbonate rock at the center of Figure 64 has slid down. No. 4 stylolite corresponds stratigraphically to the upper-central stylolite of this dolomite "horse". This proves that this horse has slid down about 25 cm and about 10 cm away from the wall of breakage.

An insoluble residue test of the clayey soft rock filling the dike-like body in the center was carried out at the Missouri Geological Survey and Water Resources following the method suggested by McCRACKEN (1949). The result shows 95% of the insoluble residues by volume consisting mostly of clay and a few grains of sphalerite and fluorite.

In thin section this clayey soft rock from the vertical vein, center in Figure 64, consists mainly of clay, fine crystalline aggregates of carbonate, a few sphalerite grains, and small euhedral quartz crystals.

Chalcedonic quartz, light brown under plain light, and fluorite fill in the spaces between the aggregates. The clayey material shows vertical laimination.

Along the sides of the channel, tongues of clay (or shale) are present. These tongues or streaks show a wavy pattern. They include or coat occasionally long and thin lenticular tongues of fluorite and/or dolomite. Also in this clay seam on both flanks of the channel, a bright luster on the conchoidally fractured surfaces of the shale which is nearly parallel to the slump surface, appears to suggest slickensided surfaces and movement. This downward movement may have been caused by a vertical pressure, produced by the load of the material filling the channel.

At the central bottom and on two places on the slope on the right, clay dikes extend downward and wedge out after 1 - 2 m. The upper half of the central clay dike consists mainly of clayey carbonate with finely disseminated small sand size grains of sphalerite. The clay dike becomes more calcareous towards its lower end, but it does not contain any visible fluorite. Megascopic examination does not suggest that this clay dike was a channel-way for "ore solutions". It rather looks like an ordinary sedimentary dike filled from above.

Whereas the lenses or tongues of dolomite can usually be connected with a definite bed of the main sequence, there is no rock corresponding to the lumps of oolitic chert anywhere on this mine wall. Therefore, it is not known whether these lumps formed in situ or whether they slid into the present position from some other previous location. At any rate, their sack-like shape may be called a gravity or geopetal feature. Therefore, it may be assumed that the chert was in a colloidal, jel-like state when the surrounding material was not yet consolidated.

Figure 66 is a microphotograph of this chert. The silica comprising the chert is microcrystalline to submicroscopic and shows a light brownish color under plain light. Some of the oolite shapes remained as well as many oolitic features which show the radial orientation of the chalcedonic silica. There are a few vertical cracks filled with pure calcite. These cracks are probably caused by tension developed during the consolidation of the silica-gel. Silica-gel in mud apparently consolidates faster than the surrounding mud, so that tensional fractures are developed. This phenomenon was described by TREFETHEN (1947). Chert occurring in this channel might display penecontemporaneous replacement, following the deposition of oolitic mud almost immediately.

The downward trend and the amplitude or thickness of the stylolites near or along the slump surface suggest that erosion and slumping took place when the dolomite beds were still in a mobile, partly unconsolidated state.

The overlying cross-bedded sandstone which is the base of the Bethel formation, did not collapse downward into the channel. Also, the undersurface of the Bethel sandstone is smooth and not corroded. Not only does this suggest that the sandstone was deposited later than the sediments filling the channel, but, these sediments were probably fairly consolidated and did not cause the overlying sediment to collapse into it.

The material filling the channel shows distinct bedding or zoning. Four zones are distinguished. No calcite and barite are present, in contrast to most other channels in this mine, and to the usual ore horizons.

A description of the zones is as follows:

Zone I: a matrix consisting of clay with admixtures of purple fluorite and "sandy" sphalerite contains roundish masses of dolomite, 2-4 cm in diameter. These masses contain some fluorite. In addition, this zone contains disoriented and broken dolomite beds and lenticules of a shale which is harder and darker than that of the matrix.

Zone II: broken pieces of dolomite beds, cemented by purple and yellowish white massive fluorite, with some clay. Both the dolomite beds and the fluorite are essentially horizontal and congruent. The transition from Zone I to II is gradual.

Zone III: mainly round and semi-round dolomite boulders, cemented by purple fluorite. Some of the boulders also contain purple fluorite.

Zone IV: whitish yellow fluorite bands (or layers) alternating with dolomite beds; both, the fluorite and the dolomite layers are more or less parallel with some irregularities (branchings, waves).

Figure 67 is a picture of a submarine slump structure occurring at the southeast end of the Oxford mine. And, Figures 68 and 69 are drawings of the same structure with detail. As shown on these Figures, the dolomite of the Renault formation and the basal sandstone of the Bethel formation, below and above the slump respectively, are not disturbed or collapsed. Also, the undersurface of the basal sandstone is not corroded.

Several stylolitic seams with wavy partings trend downward towards or into the slump surface. The amplitudes of the stylolites decrease and the thicknesses of the stylolitic seams increase as they reach the slump slope. This phenomenon is quite similar to that occurring in the slump structure shown on Figures 64 and 65. Along the upper portion of the slump surface, lenticular and long tongues of dolomite occur. They are slightly covered with dark shale which shows slickensides and polished surfaces parallel to the slump slope and parallel to the outlines of the dolomite tongues. Near the bottom of the slump, crumpled, folded, and wavy laminations of shale are abundant showing the effect of flowage. Similar features were described by CHICO (1959) in his Figures 16, 17, 19a, and 27c (thesis, Missouri School of Mines and Metallurgy).

At the bottom of the slump, the material filling the slump valley consists mainly of brittle shale and carbonate rock with disseminated sphalerite grains. It contains lenticular bodies of dolomite and a few pieces of angular to sub-angular chert which is different from the oolitic chert occurring just below the basal sandstone of the Bethel formation. Clay laminae surrounding the pieces of chert show geopetal features, as shown on Figure 69.

Dark shale which is the major material filling the slump structure impregnates the greenish shale layer about 10 cm below the sharp wedge of dolomite shown on Figure 69.

The dolomite above the shale and carbonate rock, filling the bottom of the slump, does not show distinct bedding planes and contains masses of calcite as shown on Figure 67. Below the oolitic chert layer, U-shaped fluorite bands occur. Sphalerite grains are disseminated along the lower rim of the U-shaped bands.

The oolitic chert layer is vertically fractured and filled with purple fluorite. A yellowish fluorite layer 1.5 cm in thickness occurs just above the oolitic chert layer.

Because the basal sandstone of the Bethel formation and the Renault dolomite respectively above and below the slump structure are not collapsed downward or disturbed, the time of formation should be post-depositional in regard to the dolomitic layer indicated by a horizontal stylolite seam and pre-depositional in respect to the basal sandstone of the Bethel formation. Crumpling and geopetal features of clay suggest that clay slid down and had a certain hydroplasticity at the time of formation of the slump structure. The down trend of the stylolitic seams along the slump slope suggests that the dolomite (or limestone) was partly consolidated and its compaction may not have been completed when the slump formed.

The slumping may have been caused by sub-aqueous waves, currents, or earthquake shocks, and less probably by ascending water trapped at the bottom of the present slump structure during the compaction of mud.

The origin of the calcite masses in the dolomite is not understood.

Figure 70 is a probable continuation of the same slump structure, occurring about 10 m from the slump described above.

According to EMERY (1950, p. 16-17), in the No. 4 Bethel workings of the Crystal mine, which is located about 1 km S. E. of the Deardorff mine, a northerly trending channel cut steeply into the limestone, and is filled with truncated Bethel sandstone.

Fig. 63. A slump channel exposed at a pillar, 50 m south of the shaft of Oxford mine. See the detail drawing on the next page, Figure 64.

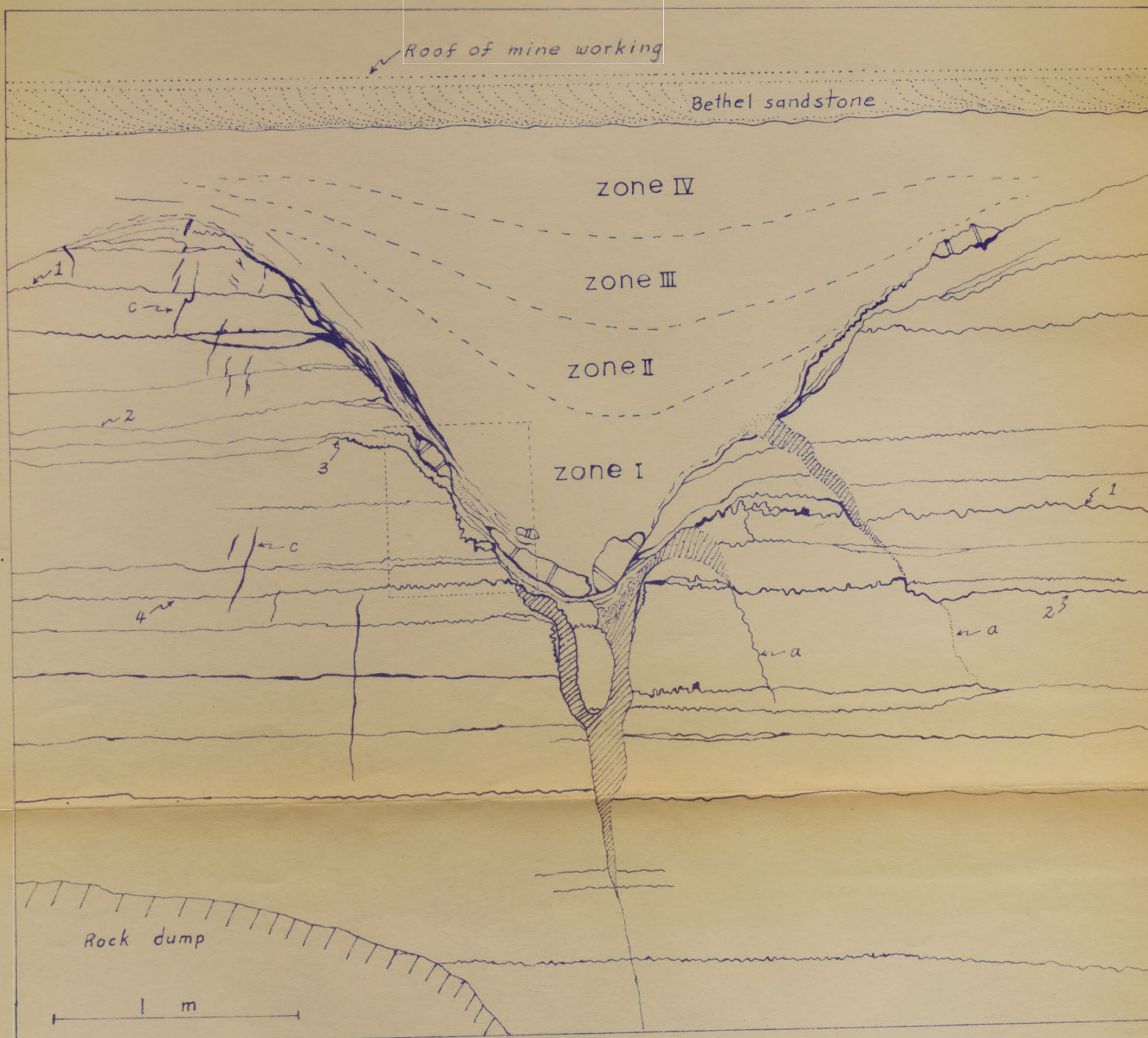


Fig. 64. Sink structure and stylolites on pillar, 50 m south of shaft, Oxford mine

	dolomite		stylolite
	cross-bedded sandstone		clay lamination
	clay carbonate rock		sphalerite sand disseminated
	chert	zone	ore channel zoned
c	calcite	a	clay tail

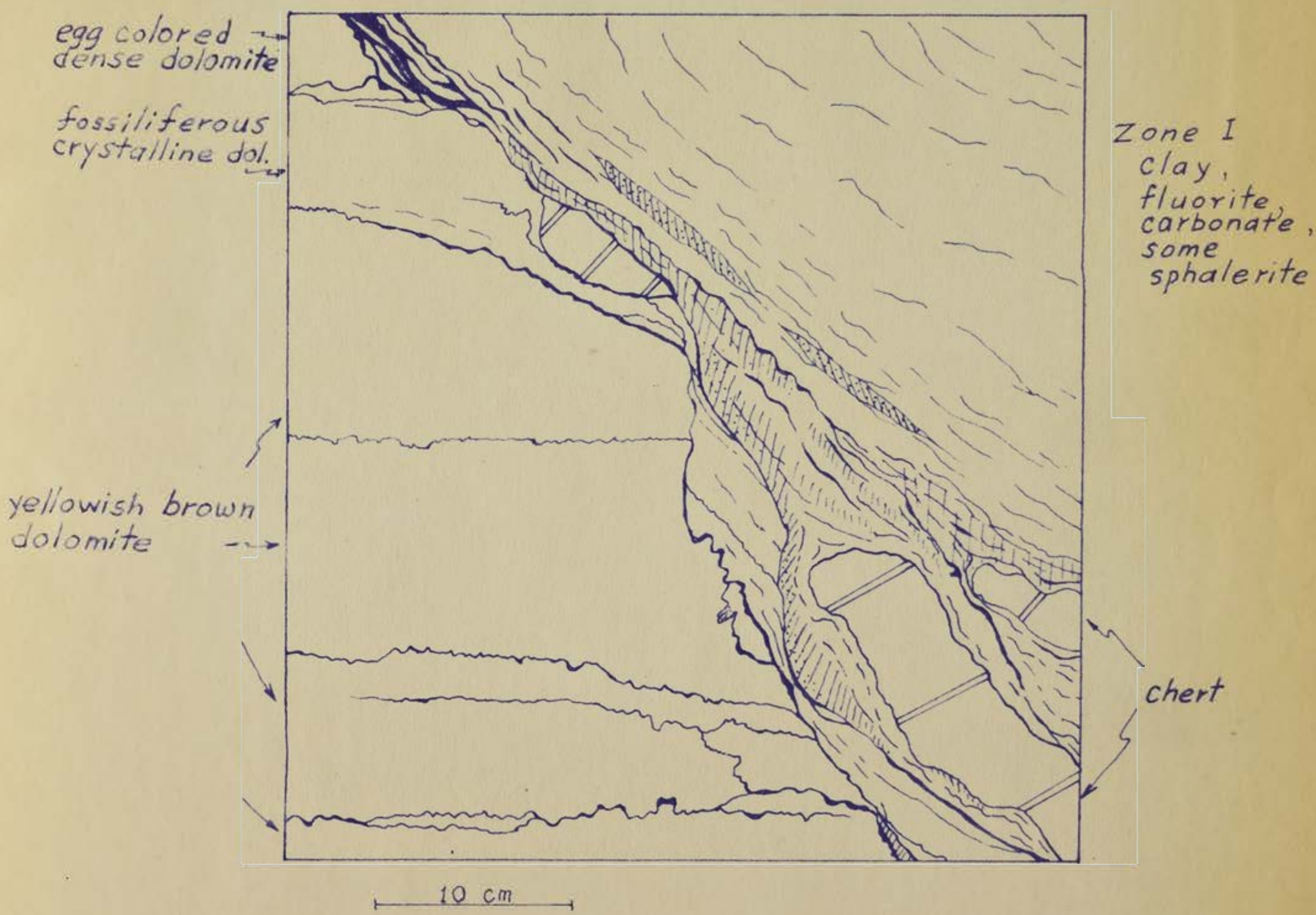
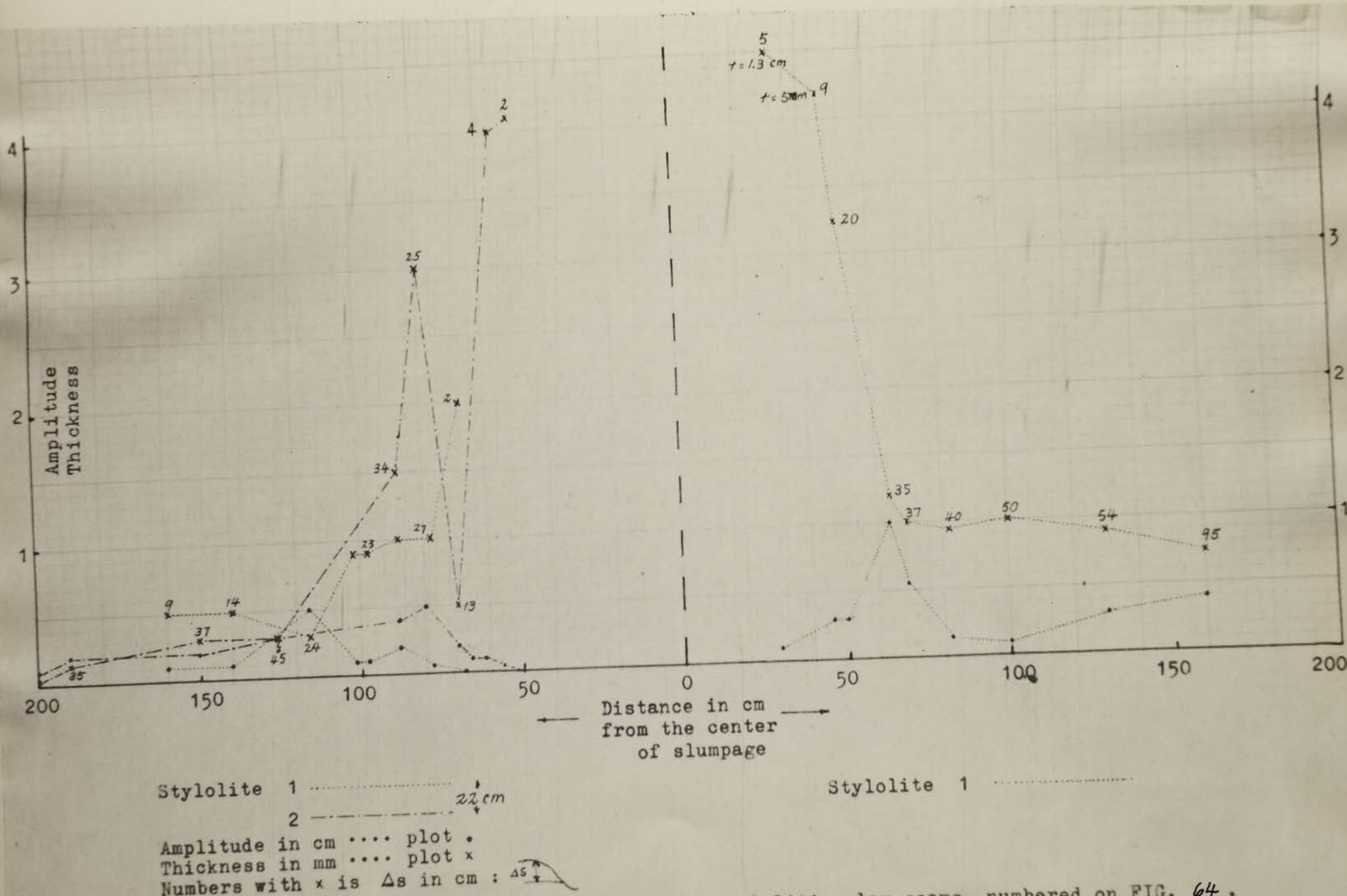
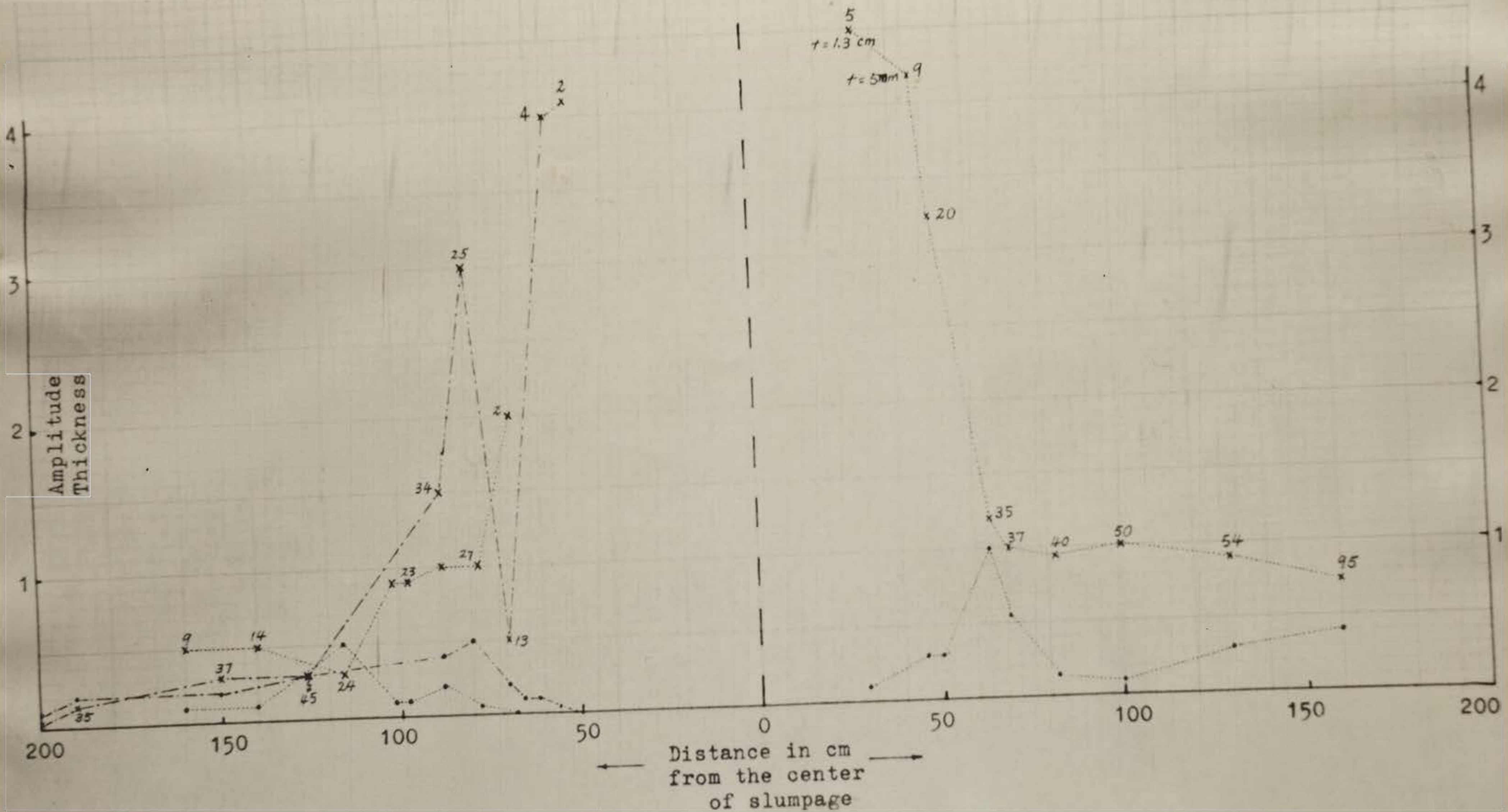


Fig. 65. Detail drawing of fig. 64 , square marked.



Graph 1. Changes of amplitudes and thicknesses of stylolitic clay seams, numbered on FIG. 64, Slumpage and stylolites, Oxford mine. See FIG. 64 .



Stylolite 1 ....

2 —·—·—·—·— 22 cm

Stylolite 1 ....

Amplitude in cm .... plot •

Thickness in mm .... plot ×

Numbers with × is Δs in cm : Δs

Graph 1. Changes of amplitudes and thicknesses of stylolitic clay seams, numbered on FIG. 64 ,

Slumpage and stylolites, Oxford mine. See FIG. 64 .

Fig. 66. Microphotograph of the chert occurring at the center of the slump-structure, on Figure 64. A piece of a fossil appears to be cut at the center by the chalcedonic "quartz". However, both sides show extinction at the same time and are probably coherent in the third dimension. An inclined fracture to the left is filled with pure calcite. Plain light; the base of the photograph measures about 1 mm.

Fig. 67. A submarine slump, occurring at the southeast end of the Oxford mine. See the detail drawings on the next two pages.

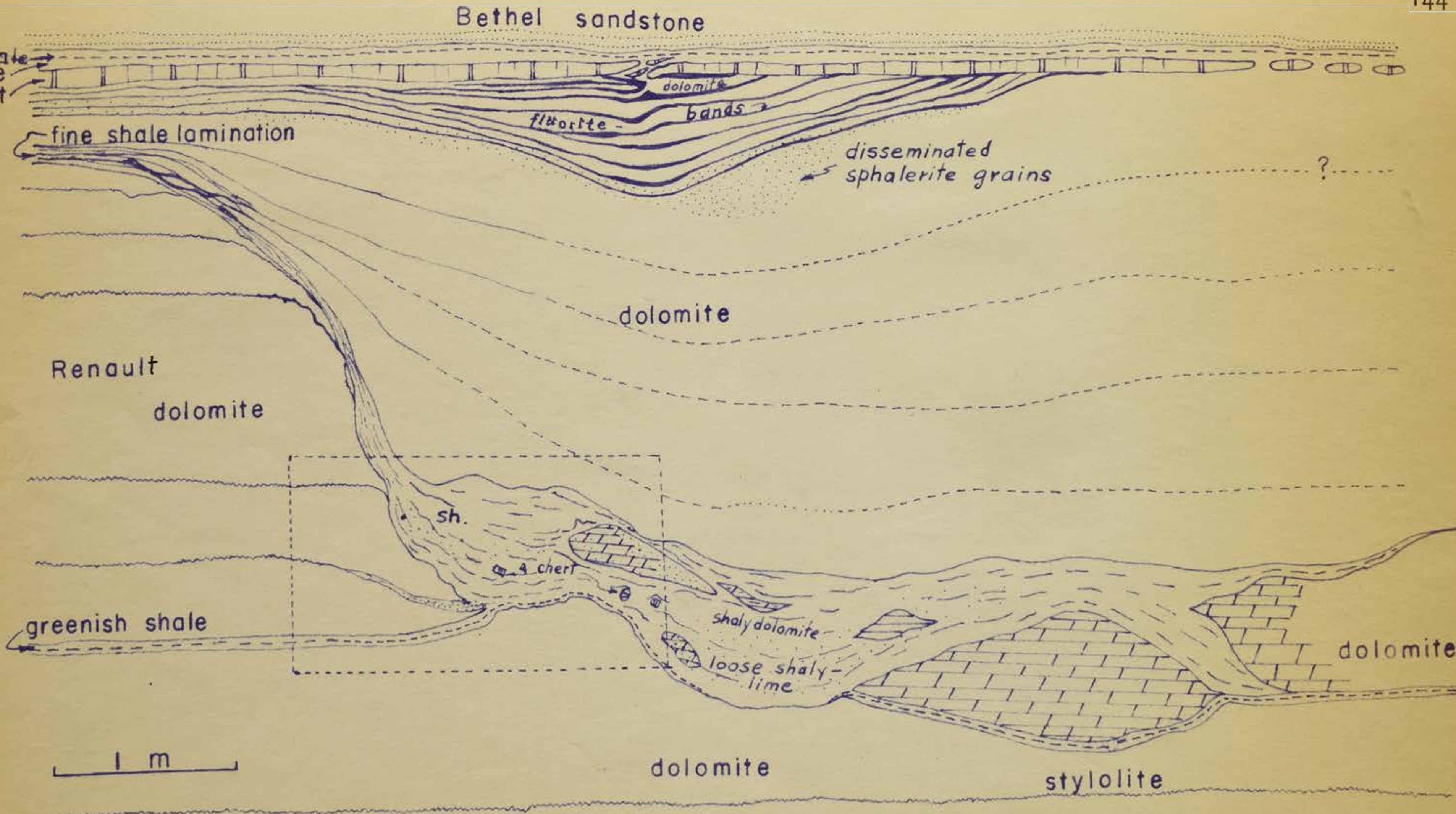
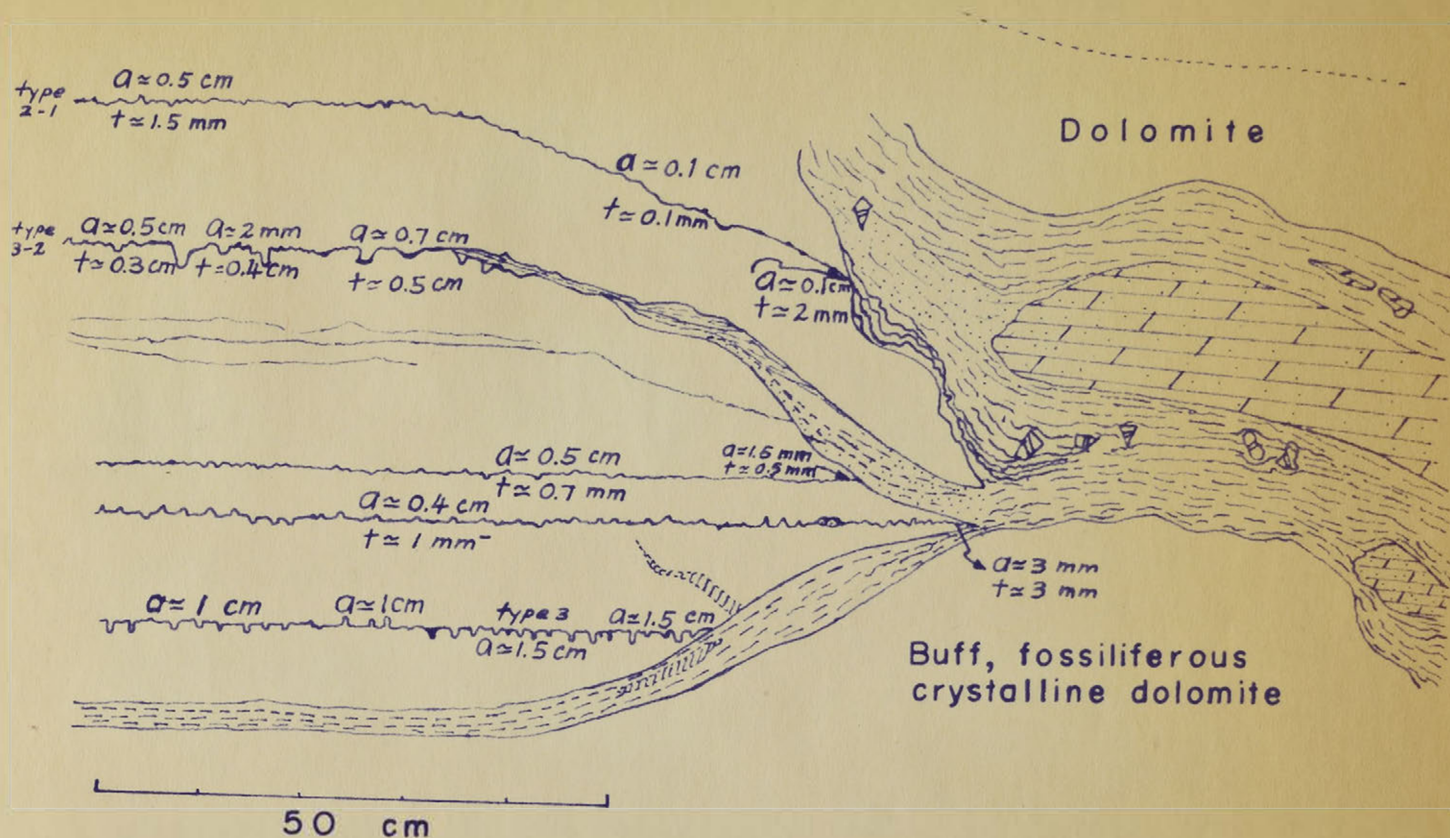


Fig. 68. SUB-MARINE SLUMP, SOUTHEAST END OF OXFORD MINE

(See the detailed drawing, square marked, FIG. 69 , next page)



Legend

- Dolomite and/or disseminated sphalerite
- Clay
- Greenish shale
- Disseminated sphalerite & sphalerite sand with clay
- Angular chert
- Calcite
- Stylolite

a : Amplitude of stylolite

t : Thickness of clay of stylolite

Fig. 69. Detail of FIG. 68, square marked, Oxford mine

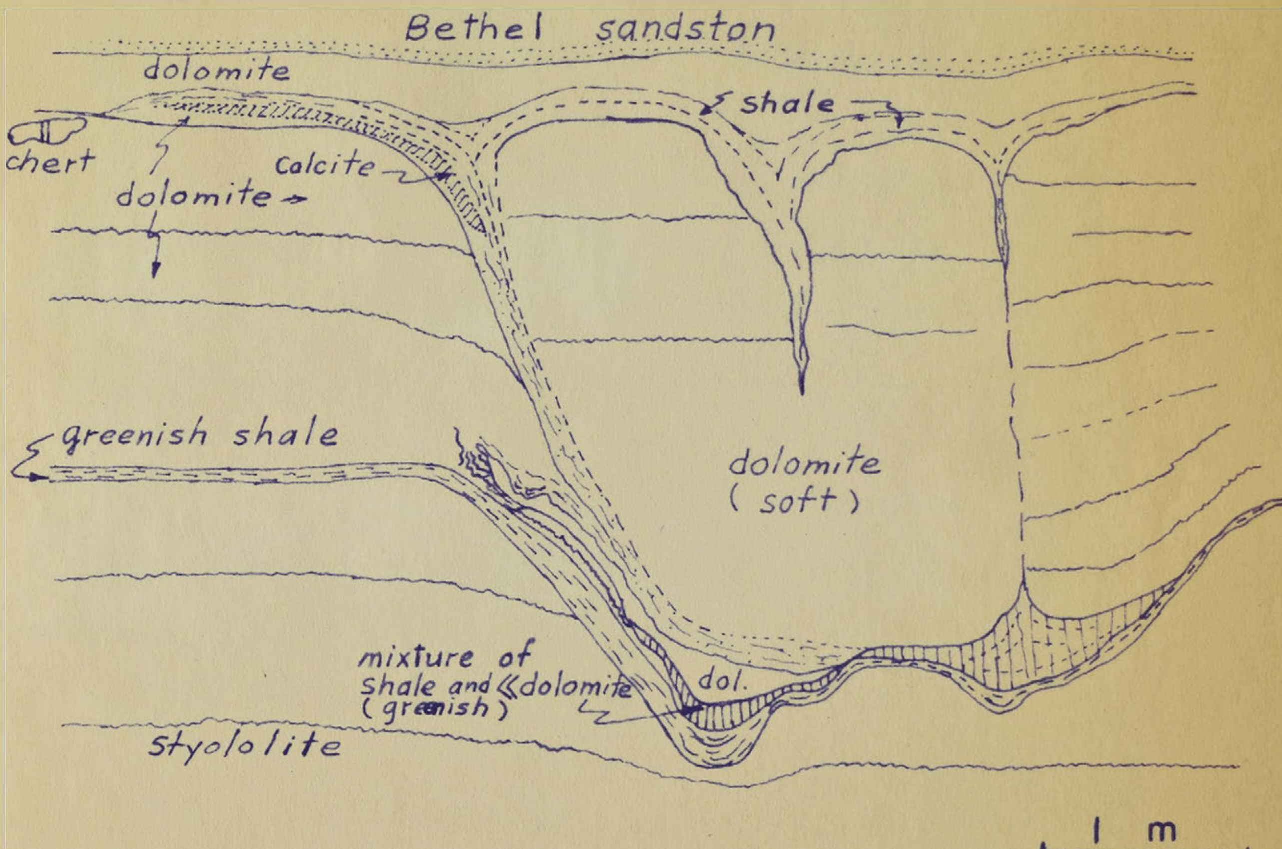


Fig. 70. Continuation of sub-marine slumping. 10 m southeast of FIG. 68, Oxford mine

5. Stylolites and compaction of sediments

As was mentioned in the previous section, the time of formation of stylolites was and is still debated in the literature. Syngenetic processes, taking place prior to and during lithification, and epigenetic processes, taking place after compaction, are both proposed.

Any interpretation should be primarily based first on detailed observations of the objects, and secondly on non-dogmatic and reasonable assumptions. Before considering any interpretation, all of the possibilities of the stylolite formation should be kept equally in mind.

The compaction of sediments, especially that of limestone (or limy mud) is inadequately understood at the present time; as WELLER (1959, p. 273) puts it: " . . . serious difficulties will remain until the lithification of limestone is more adequately understood."

Some of the major important physical and chemical changes in sediments which occur during the lithification or compaction, all of which should be considered together, are as follows, according to JONES, 1944; TAYLOR, 1950; GINSBURG, 1957; CHILINGAR, 1958; SUJKOWSKI, 1958; ILLING, 1959; WELLER, 1959; von ENGELHARDT, 1960; BAKER, 1961; etc.:

1. A great reduction of the total pore space by either compaction or cementation,

2. Partial dehydration,

3. Increase in hardness and cohesion with time,

4. Removal and precipitation of material,

5. Interstitial solution,

6. Chemical changes such as Eh, pH, concentration or elimination of certain elements, probable inversion of aragonite to calcite, etc.,

7. Other factors such as mineralogy, size and shape of the particles

electrolyses and metasomatism.

WELLER (1959, p. 298) states that observation on coarser grained fragmental sediments

> "suggests that the consolidation of limestone was accomplished at an early stage before it was subjected to the pressure of mud overburden. There are, however, exceptions to all of these observations." He continues on p. 299 "The consolidation of limestone is understood by the result of cementation. The time and conditions of the consolidation are uncertain. Some sedimentologists and geologists have suggested that all limestone consolidation took place after uplift of calcareous sediments into the subaerial zones. But it is not obvious."

SNYDER (1957, p. 925) states that "compaction of carbonate muds, probably aided by crystallization, was essentially completed under a load of 40 feet of sediments (in the southeast Missouri lead belt)."

The observations are thus as yet insufficient to understand the processes of compaction of limestone.

Regarding the source of cement in limestone WELLER (1959, p. 301) states the following:

> "Solution along stylolite surfaces might have been the source of much calcium carbonate and some limestones certainly were greatly reduced in thickness in this way but stylolites are rare or absent in many dense limestones. Also stylolites at some places can be proved to have developed after complete consolidation of the rock. Possibly much unrecognized solution has occurred along planes that did not develop stylolites and now are marked by fairly even clay or shale partings."

Figure 71 is an excellent example suggesting reduction in thickness of a carbonate bed of the Renault formation, about 2 m below the basal sandstone of the Bethel formation. Figure 72 is a close-up picture of the same structure. As shown on Figure 71, low grade fluorite bands occur above and below the carbonate layer enclosing a vertical vein and veinlets. Also in the central portion of these veinlets between displaced units, barite and fluorite bands occur without cutting the veinlets and therefore may have been there when the veinlet formed.

As shown in Figure 72, the veinlet is horizontally displaced to the left below every bedding plane relative to the upper unit of the veinlet. The bedding planes often are stylolitic. In some place the veinlet is also overlapping vertically.

The second unit of the veinlet from the top has moved to the left, dragging its top end along the stylolitic seam. The bent and crooked portion of this unit vein shows concentric fractures. Almost parallel to the larger veinlet a very thin crumpled veinlet occurs about 2 - 3 cm to the right as shown in Figure 72.

The chemical analysis (BRECKE, 1961, personal information) of the larger veinlet is as follows:

$CaCO_3$	70.60%
$MgCO_3$	16.23%
$FeCO_3$	13.16%
TOTAL	99.99%

The amount of compaction of the carbonate bed after the formation of the veinlet can be calculated in a simple manner:

Linear length of the vein	49 cm
Thickness of carbonate bed in the place of the veinlet	37 cm
Thickness of carbonate bed parallel to pencil (Figure 71)	31 cm

After this vertical veinlet had formed in the carbonate bed (perhaps sometime during the compaction of this bed), there must have taken place a reduction of at least 12 cm in thickness in the cross-section along the vein, which is 24.5% of the 49 cm presumed to be the original thickness of the carbonate bed. Also, the layer indicated by the pencil on Figure 71 underwent a reduction of 18 cm from the presumed original thickness of 49 cm, which is a 36.7% reduction in thickness.

Such amounts of masses, 24.5 and 36.7% of the original thickness, are presumed to have been reduced through the "compaction" accompanied with dissolution of carbonate rock. The dissolved carbonate may have been removed through the stylolitic seams.

Because of the physical resistance and the chemical composition of the vertical vein, the rock in the immediate vicinity of the veinlet has been reduced less in thickness compared to the layer indicated by the pencil on Figure 71. It is possible, however, that some amount of the calcium carbonate in the vein has also been dissolved during "compaction".

von ENGELHARDT (1960, p. 37) describes such a crumpled and folded vertical sandstone vein in clay shale and explains this also as a result of compaction of the clay layer.

6. Stylolites and layers of ore minerals

The stylolitic seams near or in the fluorite zones in the Illinois-Kentucky fluorspar district have been given attention by some geologists (BAIN, 1905; BASTIN, 1931; and GROGAN, 1949).

BASTIN (1931 and 1950) has reported the stylolitic seams demarcating calcite, fluorite and limestone in some of the mines from the Kentucky and Southern Illinois district. According to him, the stylolite partings separating the limestone and stylolites have served as barriers to protect the limestone from replacement by fluorite.

The stylolitic seams near or inside the layered ore mineral rock occurring at the three mines studied could be categorized as follows (a discussion is given in detail in other sub-chapters, particularly in microscopic descriptions):

(1) The stylolitic seams separating the carbonate rock and the dark siliceous carbonate rock transitional to ore mineral rocks;

(2) The stylolitic seams demarcating banded fluorite, sphalerite, barite, and calcite from limestone;

(3) The stylolitic seams inside the fluorite and sphalerite bands of which the amplitude is generally low and may change laterally into shale partings;

(4) The stylolitic seams developed horizontally in the carbonate rocks, gradually disappear or degenerate megascopically near the cross-bedded bands of ore minerals.

Fig. 71. Carbonate veinlet deformed during compaction. A close-up photograph is given in the next Figure. The white line to the right is a pencil which is 13 cm long. The whitish horizontal layers consist of fluorite and some barite.

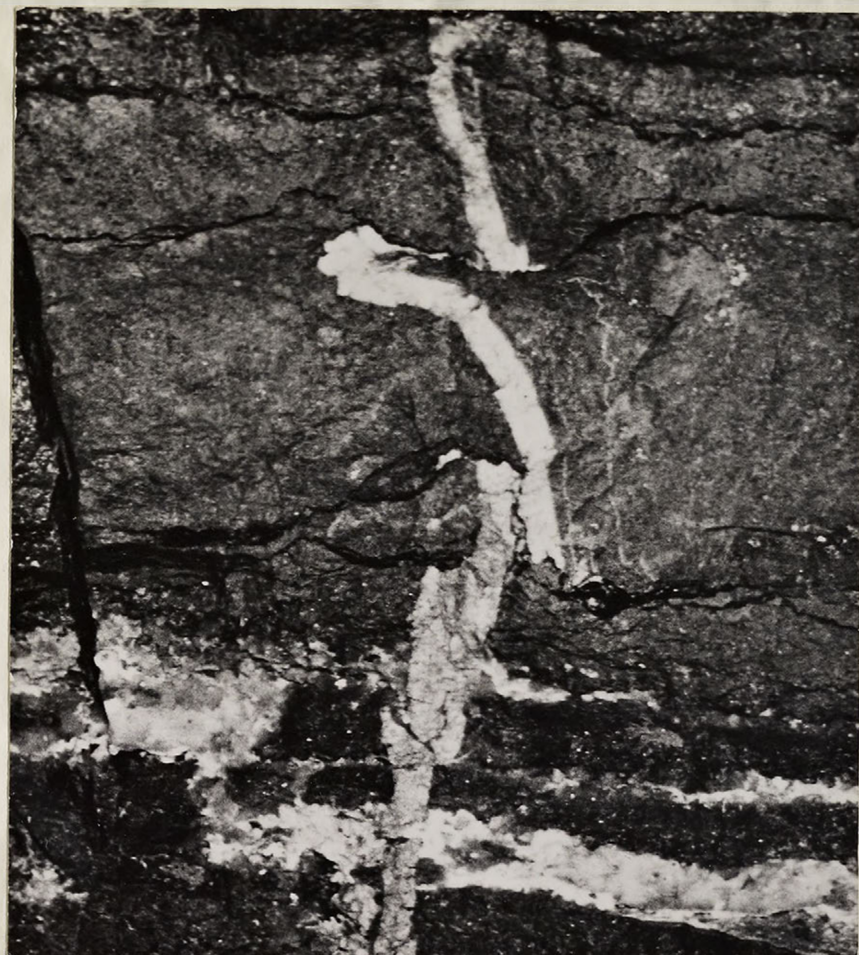


Fig. 72. Detail of Figure 71. Veinlet formed during compaction; note the very tiny parallel veinlets in the third layer in the upper half of the photograph; these tiny veinlets illustrate the same mechanism as does the thicker main vein. The thickness of the latter is about 1 cm.

7. Microscopic observations of the stylolite seams

Despite CAYEUX's (1935) statement that for an understanding of stylolite forming processes, microscopic studies and experiments are absolutely necessary, very few investigators, even after 1936, used thin sections. Among these few were CONYBEARE (1949), BASTIN (1951), BLOSS (1954), HEALD (1955,59), BROWN (1959), THOMSON (1959) and GOLDING (1959, 60, 62). The work by CAYEUX, which he summarized in the 1935 textbook, still stands out as the leading step towards a better understanding of the formation of stylolites.

As summarized in the literature review, all of these microscopic studies refer to some special feature or composition, except perhaps HEALD (1955, 59), who investigated stylolites in sandstones in a fairly comprehensive way. Carbonate rock stylolites were, therefore, never studied extensively, to the knowledge of the present writer. Some of the textbooks (GRABAU, 1913; TWENHOFEL, 1926; SHROCK, 1948; PETTIJOHN, 1956; ROCHIN, 1958; CAROZZI, 1960) discuss stylolites with occasional reference to microscopic observations, but again only very briefly and in a sketchy way.

An attempt was therefore made in this thesis to offer a more comprehensive discussion of microscopic observations. A main reason for such a detailed treatment was the possible close relationship between the genesis of stylolites and the genesis of the ore minerals. This sub-chapter contains only the descriptions of the individual thin sections. The observations made are summarized in sub-chapter 8.

The specimens are numbered as S-1, S-2, etc. Whenever two or more sections were made of one specimen, the thin section number is given as follows: S-1-1, S-1-2, etc.

Sample no.: S-1-1 Location: Hill mine

Stratigraphic horizon: lower Fredonia

Megascopic observation: Whitish grey oolitic limestone. Inclined stylolite, type 2, infilled or lines with purple fluorite; cuts horizontal stylolite of type 6.

Microscopic observation (stylolite section):

Rock below stylolite: Oolitic limestone; some oolites contain fossils which include microcrystalline quartz at their center. Euhedral quartz crystals are scattered through many oolites. Oolites are cemented with later calcite which locally corrodes some oolites. Galena replaced outer rims of oolites (Figure 116).

Rock above stylolite: Oolitic limestone; only a part of the oolites contain fossils; the oolites are cemented with calcite and rarely with quartz. Euhedral quartz crystals (average length = 0.1 mm) occur inside the oolites; but some quartz rests across the calcite veinlets. There is authigenic quartz in the calcite cement.

Stylolitic seam:

Seam material: Limonite stained clay (?) is thicker at the crest or valley of the seam than in vertical portions.

Quartz: A considerable number of euhedral-subhedral quartz grains (average length = 0.1 mm) occurs along with the limonite stained clay (?) and the number of quartz grains is much higher along the crest or valley than along the vertical seam.

Fluorite: Fluorite occurs in spots along the stylolitic seam. It is thicker at the crests and valleys and makes sharp boundaries with the oolites.

Calcite: Coarse crystalline calcite occurs frequently along the crest or the valley. Some calcite along vertical seams shows striations which in part may consist of pressure twins.

Host rock: Oolites above and below the stylolitic seam are sharply cut.

Sample no: S-1-2 Location: Hill mine

Stratigraphic horizon: lower Fredonia

Megascopic observation: Whitish grey oolitic limestone.

Stylolite is type 6 class.

Microscopic observation (stylolite section):

Rock below stylolite: Oolitic fossiliferous limestone; it is cemented with secondary calcite. Quartz grains occur inside the oolites and some of quartz grains have grown to euhedral form. Some oolites are cut by later calcite veinlets.

Rock above stylolite: Oolitic fossiliferous limestone; quartz crystals (average length = 0.1 mm) occur inside the oolites. It is cemented with clear calcite.

Styloitic seam:

Seam material distribution: It is accumulated much more at the crests or valleys.

Quartz: Quartz accumulation is not distinct in this case, even though a small number of quartz crystals is scattered inside the oolites.

Fluorite: It does not occur.

Calcite: Not always, at the crest and the valley secondary calcite crystals occur. Some clear calcite occurring parallel to and along with the vertical seam shows striations.

Galena: Inside a cubic crystal, concave shaped calcite occurs; probably dark grey rims of oolites and interstitial calcite are replaced by galena and light grey calcite at the inner cores of oolites is left.

<u>Host rock:</u> Above and below the seam, oolites are sharply cut by the stylolitic seam.

Sample no.: S-1-3 Location: Hill mine

Stratigraphic horizon: lower Fredonia

Megascopic observation: Whitish grey oolitic limestone. Stylolite is type 6 class.

Microscopic observation (stylolite section):

Rock below stylolite: Cementation of oolites is relatively loose; they contain many more quartz crystals than those in the lower portion. Quartz in oolites is euhedral (average length = 0.05 mm) and quartz outside oolites is microcrystalline.

Rock above stylolite: Oolites are relatively well compacted. Cemented by calcite and also by secondary micro-quartz. Only few oolites enclose quartz grains.

Stylolitic seam:

Quartz: It occurs along the crests or valleys either as a submicroscopic mass or microcrystalline mass (average diameter = 0.0 - 0.05 mm).

Fluorite: It only occurs inside or outside the crest portion of the clay seam. It often occurs around or near the quartz. In some cases, round grains of fluorite (diameter 0.1 mm) occurs at a distance 1 mm from the seam in the cementing calcite.

Calcite: Secondary coarse crystalline calcite occurs sometimes along the crest. Calcite occurring along vertical seams is very thin. Boundaries between coarse crystalline calcite and submicroscopic quartz inside the stylolitic valley are stylolitic (Figure 73).

Oolites: Above and below the seam as well as along the wall, they are sharply cut, either by microfaults or corrosion.

Fig. 73. Sample S-1-3. Oolitic limestone. Sub-Rosiclare horizon. crossed nicols, base of photograph = 0.9 mm. Stylolitic boundaries between secondary coarse crystalline calcite and submicroscopic quartz at the inner side of a stylolitic valley.

Sample no.: S-1-4 Location: Hill mine

Stratigraphic horizon: lower Fredonia

Megascopic observation: Whitish grey oolitic limestone. Stylolite is of type 2. Calcite veinlets cut the rock but not the stylolite; a displacement of 13 mm may have taken place along the stylolitic seam before consolidation. The seam often consists of several smaller seams. Figure 74 is an enlarged direct one-to-one photograph of the thin section.

Microscopic observation (stylolite section):

Rock below stylolite: Oolites are closely packed relative to the upper rock. There are two kinds of authigenic quartz crystals; 1, euhedral quartz (av. length = 0.05 - 0.10 mm) inside or cutting across the oolites (more frequently than in the upper rock), 2, allotriomorphic quartz grains which cement oolites.

Rock above stylolite: Oolites are mainly cemented with clear calcite. Euhedral quartz crystals (av. length = 0.12 mm) occur mostly inside the oolites but also cutting across. The number of them is smaller than in the rock below the seam.

Stylolitic seam:

Quartz: 1) A considerable number of euhedral quartz grains occur along the stylolitic seam, actually filling the bulges of the stylolite "meander", which are wide at the crests and valleys. Most of these crystals are elongated and oriented parallel to the nearest side of the seam (Figure 75). 2) Around one of the quartz grains, a later zone of quartz has grown and produced euhedral form. 3) Submicroscopic quartz or perhaps chalcedonic material occurs in a few places in bulges within the seam. 4) Under high magnification, two euhedral quartz crystals (length = 0.21 mm) just below the seam (0.1 mm) show a small amount of the same dark stylolitic seam material only at the bottoms and the crystallographic faces have disappeared.

Fluorite: Occurs randomly along the seam and much more at the inner side of the peaks. Texturally, fluorite has three positions; a, it fills the space between walls of the seam, occasionally looking like a veinlet, where this space is vertical or nearly vertical; b, it occupies the same space as the cementing calcite. In both cases it is always near the stylolite seam; and c, very rarely does fluorite occur within oolites.

Calcite: Coarse crystalline calcite frequently occurs at the inner side of the peaks. Calcite veinlets, above mentioned cut the host rock and its oolites. They also cut the thick fluorite "veinlet" or portion in the stylolite seam (see Figure 74), which suggests that the calcite veinlets formed after this fluorite body.

Oolites: Two oolites in the valley show stylolitic contact and these oolites at their contact have been dissolved.

Calcite veinlets: The calcite veinlets in this slide appear to match each other below and above the stylolite seam. However, this may be entirely fortuitous. There is a difference of distance of 0.4 mm between the two distances between the divergent branches. There is no clear evidence for a movement of 13 mm to have offset the veinlets, although this possibility can not be dismissed.

As to the time of formation of the veinlets it can be said that they must have formed after the fluorite "body" or "veinlet" to the left in Figure 74. This fluorite "veinlet" appears to have undergone fracturing at the time it was cut by the calcite veinlet. The frequent optical continuity of the veinlets with the cementing calcite suggests that deposition of this matrix calcite had not terminated when the veinlets formed, although it must have been started in order to have given the rock a certain rigidity.

Fig. 74. Sample S-1-4. Enlarged direct photograph of the thin section. Base line of the photograph is about 2.4 cm. f = fluorite and c = calcite.

Fig. 75. Sample S-1-4. Oolitic limestone, lower Fredonia limestone. x nicols, base of photograph is 2.4 mm. Quartz accumulation at the inner side of a stylolitic crest.

Sample no.: S-2-1 Location: Hill mine

Stratigraphic horizon: upper Fredonia

Megascopic observation: Below stylolite: Whitish grey limestone.
Above stylolite: Limestone with disseminated sphalerite, purple fluorite and barite. "Enclosure" of the lower rock pieces in the stylolitic seam.

Microscopic observation: (stylolite section):

Rock above stylolite: Fossiliferous and oolitic limestone. Euhedral quartz crystals are scattered through. Vertical calcite veinlets cut oolites and are terminated by the stylolite.

Rock below stylolite: Calcite, dolomite (?), fluorite, quartz sphalerite, and barite in a variable, often coarse intergrowth. Quartz: 1) Euhedral crystals (av. length = 1 mm) with inclusions occur as common disseminations. 2) Very fine grained patches of quartz (?) occur near fluorite. Calcite or dolomite: Occurs in a mosaic or irregular intergrowth with quartz, fluorite and barite. Often it is quite large and almost always clear and frequently euhedral grains are seen. Fluorite: It occurs between calcite or along with sphalerite grains and contains inclusion of the other minerals. Sphalerite: Displays granular shape; often includes quartz and calcite which therefore are earlier. Barite: Occurs in the higher portion of the section and shows excellent plumose patterns.

The paragenesis chart of this portion of the rock is as follows:

```
qt   __________ - - -
ba           - __________ - - -
ct                   __________ - - -
sl                            __________
fl                                      __________
```

(qt = quartz, ba = barite, ct = calcite, sl = sphalerite and fl = fluorite)

Stylolitic seam: Consists of dark brownish material (composition unknown) mixed with submicroscopic (or cryptocrystalline) quartz (?). It also includes small grains of quartz (smallest size 7.5 micron in diameter) which shows a transition into dark brownish material. This material occurs along the upper part of the seam and is greatest at the peaks. The lower part of the seam has less or in some parts has no dark brownish material, but a considerable number of quartz crystals occur.

Fluorite: Occurs close to the seam, but is not seen within.

Quartz: A considerable number of subhedral quartz crystals with inclusions occurs along the lower part of the seam, particularly within the bulges. There is a distinct tendency of quartz to be oriented parallel or sub-parallel to the lower rim of the seam. However, this seam itself is often irregular.

Host rock: Inside the seam, a piece of the lower host rock is seen; an oolitic remnant is observed and it shows almost the same dark color under plain light as the lower rock; but it contains fewer quartz crystals than the lower host rock. Oolites in the lower host rock are cut by the seam.

Sample no.: S-2-2 Location: Hill mine

Stratigraphic horizon: upper Fredonia

Megascopic observation: Same as S-2-1

Microscopic observation (stylolite section):

Rock below stylolite: Fossiliferous oolitic limestone. Euhedral to subhedral and submicroscopic quartz grains occur. The latter is rare and seen in oolitic core. Most of the coarse quartz grains do not contain impurities in them.

Rock above stylolite: Calcite, dolomite (?), fluorite, quartz, sphalerite and barite in variable intergrowths. A baritic band (av. thickness = 1 mm) with plumose pattern occurs and does not follow the stylolitic seam. Idiomorphic fluorite crystals on or around calcite occur in this baritic band (Figure 76). Some fluorite cubes show some whitish lines along cleavage planes under crossed nicols.

The paragenesis chart of this portion of the rock is as follows:

```
qt    ___________
ct                 __________
fl                            ___________
ba                                  __________
```

(qt = quartz, ct = calcite, fl = fluorite, and ba = barite)

Stylolitic seam: Most dark brownish material (probably containing much submicroscopic, cryptocrystalline quartz) occurs at the upper rim of the seam. A considerable number of subhedral quartz grains with interstitial dark brownish material occur along the lower part of the seam; scarce fluorite grains also occur along the seam. Submicroscopic cryptocrystalline silica (?) streaks show orientation parallel to the side wall of the seam and are optically continuous with some of the clear quartz grains enclosed in them.

Fig. 76. Sample S-2-2. Oolitic limestone, upper Fredonia formation. crossed nicols, base of photograph = 2.4 mm. Plumose pattern of barite and fluorite cubes (black) grown on crystalline calcite.

Sample no.: S-3-1 Location: Drill core from Hill mine

Stratigraphic horizon: upper Fredonia (core sample)

Megascopic observation: Whitish grey oolitic limestone. Stylolite is of type 4-2 class. Figure 77 is an enlarged direct one-to-one photograph of the thin section.

Microscopic observation (stylolite section):

Rock on one side of stylolite: Oolitic fossiliferous limestone. Oolites are cemented with relatively clear calcite and rarely with microcrystalline quartz. Only a few oolites contain small quartz crystals.

Rock on the other side of stylolite: Oolitic limestone. Contains many more dark impurities and the cementing calcite is also impure. Few quartz grains present.

Stylolitic seam:

Dark seam material: Is thickest at the inner sides of the stylolitic "valley" (?) and shows lamination parallel to the rim of the seam. Probably the bulk of material showing brownish stain may consist mainly of submicroscopic, cryptocrystalline silica. Some grains are large enough to allow a determination as quartz, which supports the idea of the remainder also being quartz. The cryptocrystalline material occurs in streaks with parallel to subparallel orientation to the nearest sides of the seam.

Quartz: Few relatively clear and allotriomorphic grains and submicroscopic quartz occur along the seam. The brownish material in some places bends around the grains, whereas in other places it ends at the grain boundary.

<u>Fluorite:</u> May occur along portions of the seam, but could not be recognized with certainty.

<u>Calcite:</u> 1) Calcite enclosed in the seam often shows a mosaic-type intergrowth pattern of very small size; 2) "secondary" coarse crystalline calcite areas occur at the inner side of the stylolitic valley; and 3) coarse crystalline calcite "flags" occur along the vertical seam and show almost vertical striations or slickensides. These indicate "micro-faults" which are slightly inclined towards the inner side of the "valley" (?). Also some are slightly curved (Figure 78). These striations are probably due to pressure-twinning which developed during the downward movement of the host rock inside the column.

<u>Host rock:</u> Both, the upper and the lower rocks are sharply cut by the seam. One small up-peak (?) of a stylolitic column is developed with a sharp cut into the inner column of rock, departing from the main seam; an ovoid oolite was apparently pushed down over it during diagenesis. This small up-peak is somewhat wider in the middle (Figure 79).

Fig. 77. Sample S-3-1. Enlarged direct photograph of the thin section. The base of the photograph about 2.5 cm. Figures 78 and 79 are microscopic details of the stylolitic seam shown in this photograph.

Fig. 78. Sample S-3-1. Oolitic limestone, upper Fredonia limestone (core sample). +nicols, base of photograph = 1.2 mm. Detail of Figure 77 (location: center of the left wall of stylolite "valley"). Secondary crystalline calcite "flag" along the vertical section of the stylolitic seam shows striations indicating a microfaulting. Left on the vertical seam is the inner side of the stylolitic column.

Fig. 79. Sample S-3-1. Oolitic limestone upper Fredonia limestone (core sample). Parallel nicols, base of photograph is about 1.2 mm. (Detail of Figure 77: Right bottom of stylolite valley). An ovoid oolite is cut by a small up-peak (?) stylolite. Note also that oolites are cut by the seam: an ovoid oolite on the right by the main seam and four oolites inside the up-peak (?) stylolite.

Sample no.: S-3-2 Location: drill core from Hill mine

Stratigraphic horizon: upper Fredonia (core sample)

Megascopic observation: Whitish grey oolitic limestone

Microscopic observation (stylolite section):

Host rock: Same as sample S-3-1

Stylolitic seam:

Dark seam material: Layers of this material orient parallel to the wavy seam itself. A considerable amount of the dark material, also with parallel orientation to the seam, occurs at a certain portion where the seam displays curves or bulges. In some other cases it shows fluidal texture, sometimes with distorted and rotation-like orientation.

See description of S-3-1 on the probable composition of the dark brownish material.

Quartz: 1) Quartz grains are enclosed in the dark seam material. The size of the anhedral quartz grain varies. Microcrystalline subhedral quartz grains enclosed in the dark seam material average 0.015 - 0.03 mm in diameter; intergranular spaces occasionally contain almost only submicroscopic cryptocrystalline silica (?). 2) Submicroscopic, cryptocrystalline and fibrous silica (?) is oriented parallel to the dark wavy laminae and probably is the main constituent between the dark brownish seam material which may often only be a stain or very minute skins, the composition of which may be organic material accumulated during stylolite formation.

Fluorite: May occur along portions of the seam, but was not recognized with certainty.

Calcite: 1) Calcite, which is essentially the same as that in lower (?) host rock, shows small grained (0.01 - 0.005 mm) mosaic texture and often contains an intergranular substance which has the same color as the dark oolitic "calcite" and is presumably of organic nature (CAROZZI, 1960, p. 244). 2) Clear matrix calcite shows extremely intensive striations (minimum distances between the adjoining striae are less than 2.5 micron).

Host rock: The oolites and fossils are cut on both sides from the seam.

Geometric seam features: The present sample is from a drill core and top and bottom are actually not known. However, the trends of the streaks of the brown, perhaps bituminous stylolite material, reveal the possible orientation. The fine grained darker oolite rock pierces into the coarse grained oolite rock and apparently has "smeared downward (?)" portions of the dark stylolite material.

If we assume that the upper rock was more fluid, i.e., less indulated, it is logical to conceive that gravity has been the driving force of this intrusion. Therefore, this direction of the drag may be considered to be a top-bottom indicator.

If the "upper" rock has actually pushed downward, one could expect to see an extension of the wall of the "finger" in the "upper" rock. This is the case. An indistinct fault extends into the "upper" rock and close to the shoulder of the "finger", a "snow-ball" pressure-twin occurs exactly where friction and rotation of the oolites during downward movement would be expected.

Sample no.: S-4-1 Location: Southeast end of the Oxford mine

Stratigraphic horizon: Renault limestone (upper)

Megascopic observation: Massive brownish limestone. Stylolite is of type 1-2 class. The calcite veinlet has been slightly displaced. Figure 80 is an enlarged direct photograph of the thin section.

Microscopic observation (stylolite section):

Rock below and above stylolite: Fossiliferous limestone; most of the fossils are crinoids. Microcrystalline and chalcedonic quartz rarely occurs inside the oolites. Some chalcedony shows radial extinction with fibers.

Stylolitic seam:

Dark seam material: It is rather uniform in thickness along the seam and shows lamination. One circular fossil (?) has been preserved in the bottom of a stylolitic valley (Figure 81).

Quartz: Chalcedonic and microcrystalline quartz occur as a main constituent of the seam material, and the dark colorization is probably the result of staining by the seam material of unknown composition.

Fluorite: Not observed.

Calcite: The calcite enclosed inside the seam is impure.

Calcite veinlet: Cuts host rock sharply. The main stylolite does not continue into this vertical veinlet, whereas a small band of submicroscopic and fibrous quartz (?) continues from the main seam penetrating the grain boundaries of the coarsely crystalline calcite and running parallel to them. Calcite crystals between the discontinuous stylolite sections contain impurities (probably submicroscopic pieces of crushed material (?)

and microcrystalline or fibrous silica). The calcite crystals show "striations" roughly parallel to the seam horizon. These striae correspond essentially to the same direction or angle as primary cleavage surfaces of calcite grains. These striae are much more intensive along the stylolitic horizon (Figure 82).

<u>Host rock:</u> Both sides, above and below the stylolite are cut.

Fig. 80. Sample S-4-1. Enlarged direct photograph of the thin section. The base of the photograph measures about 2.5 cm.

Fig. 81. Sample S-4-1. Fossiliferous limestone, Renault limestone. + nicols, base of photograph = 1.5 mm. A circular fossil (?) has been preserved in a stylolitic valley. Lower part of this oolite has slightly corroded and the upper portion is also stylolitic. Seam is thicker and encloses many more grains of quartz of microscopic size at the bottom and top of this oolite than the sides. Seam is essentially composed of submicroscopic and fiberous silica and black material stained in it. A fossil (?) has been cut by the seam to the lower right.

Fig. 82. Sample S-4-1. Fossiliferous limestone, Renault limestone. + nicols, base of the photograph = 1.35 mm. Pressure twin of coarse crystalline calcite as an extension of a stylolitic horizon, which is the horizontal center of photograph. Calcite vein above stylolite moved slightly to the left. Cleavage lines are very close at the stylolitic horizon; the intensity of cleavage decreases above and below the stylolitic horizon. It may in part consist of pressure-twins due to shear stress which may be related to stylolitization.

Sample no.: S-4-2 Location: Southeast end of Oxford mine

Stratigraphic horizon: Renault formation (upper)

Megascopic observation: Massive brownish limestone. Calcite veinlet is displaced about 1.6 mm by a stylolite of the type 2-5 class.

Microscopic observation (stylolite section):

Rock above and below stylolite: Fossiliferous limestone with "impurities" (much silica, some of it fibrous when seen under 45 x 10 magnification). Round grains of quartz, commonly in aggregates, occur in the center of the coarse crystalline calcite grains and of the relatively clear oolites or fossils, occasionally showing radial and fibrous extinction. In some cases, the later secondary (?) calcite has grown around the silica spherulites or granules. Some of the fossils consist of a mixture of calcite and submicroscopic, cryptocrystalline and fibrous silica (could only be seen under high magnification).

Stylolitic seam:

Dark seam material: It essentially is composed of submicroscopic, cryptocrystalline and fibrous silica (?). Granules of crystalline quartz (10 micron in av. dia.) are enclosed in the dark stained material (silica ?). The orientation of this fibrous and submicroscopic silica (?) is essentially parallel to the rims of the seam.

Fluorite: Not observed.

Calcite: Rarely enclosed in the seam as small pieces. No secondary calcite is seen along the periphery of the seam.

Calcite veinlet: Horizontal displacement corresponds its width and is about 1.2 mm and vertical displacement about 2 mm. Along the displaced portion and near the stylolite, submicroscopic and fibrous silica (?) occurs; the latter is not thick compared to the main seam. In this case, no "striations" are seen in the calcite as in S-4-1.

Sample no.: S-5-1 Location: Hill mine

Stratigraphic horizon: upper Fredonia

Megascopic observation: Whitish buff oolitic limestone. Stylolite is of the type 3 class. Figure 83 is an enlarged direct photograph of the thin section.

Microscopic observation (stylolite section):

Rock above and below stylolite: Oolitic limestone; clear "dog-tooth" calcite surrounds the oolites radially, apparently representing the first generation of the matrix minerals. Euhedral quartz occurs rarely inside the oolites. Some quartz grains of probably detrital origin in the cementing calcite have grown secondarily into euhedral forms. Microcrystalline quartz has probably crystallized at a later time.

Styloltic seam:

Dark seam material: Scattered through the seam and does not show distinct lamination. The composition of this dark material is not known, but it is essentially mixed with submicroscopic and fibrous (or amorphous?) silica (?).

Quartz: Quartz grains (av. dia. = 0.1 mm) are accumulated along the stylolite seam and even much more so at the crests and valleys (Figure 84). These grains are of almost the same size as those in the host rock and include no impurities. Again, the quartz grains are surrounded usually by the brownish seam material. Most of the quartz grains show a peculiar undulation.

Calcite: Secondary coarse crystalline calcite occurs at the inner side of the crest. The vertical portion of the largest crest is bordered by a calcite seam which shows striations, the lines of which are slightly inclined toward the inner side of the stylolitic column. These striations again are most probably pressure twins.

Fluorite: A small fracture cuts across the lower left of the slide in photograph Figure 83 and apparently is filled mostly with CaF_2 (see Figure 85). The thickness of this veinlet is 0.05 - 0.1 mm. It does not follow the seam; it spreads out laterally cutting the seam, the oolites, and the cementing calcite. In this respect, the formation of fluorite in this portion of the rock took place later than the deposition of the latest cementing calcite and also later than the formation of the stylolite.

Host rock: Both sides are sharply cut.

Insoluble residue study: The rocks on both sides of the stylolite were carefully prepared (cut) not to include or to be contaminated by any stylolitic seam material. These two pieces of rock were treated in a 50% HCl solution at the Insoluble Residue Laboratory of the Missouri Geological Survey and Water Resources. The residues were collected according to McCRACKEN's method (1949). The results were as follows:

	Original sample wt. (gm)	Wt. of residue (gm)	Wt. % of residue
Rock above the seam	18.2	0.6134	3.4
Rock below the seam	5.5	0.1711	3.1

Results of the microscopic examination of these insoluble residues in both cases indicate a composition of about 40% euhedral quartz and 60% "clayey material" by volume. An x-ray analysis of the "clayey material" will be required in order to be sure about the possible presence of other minerals or hydrocarbons.

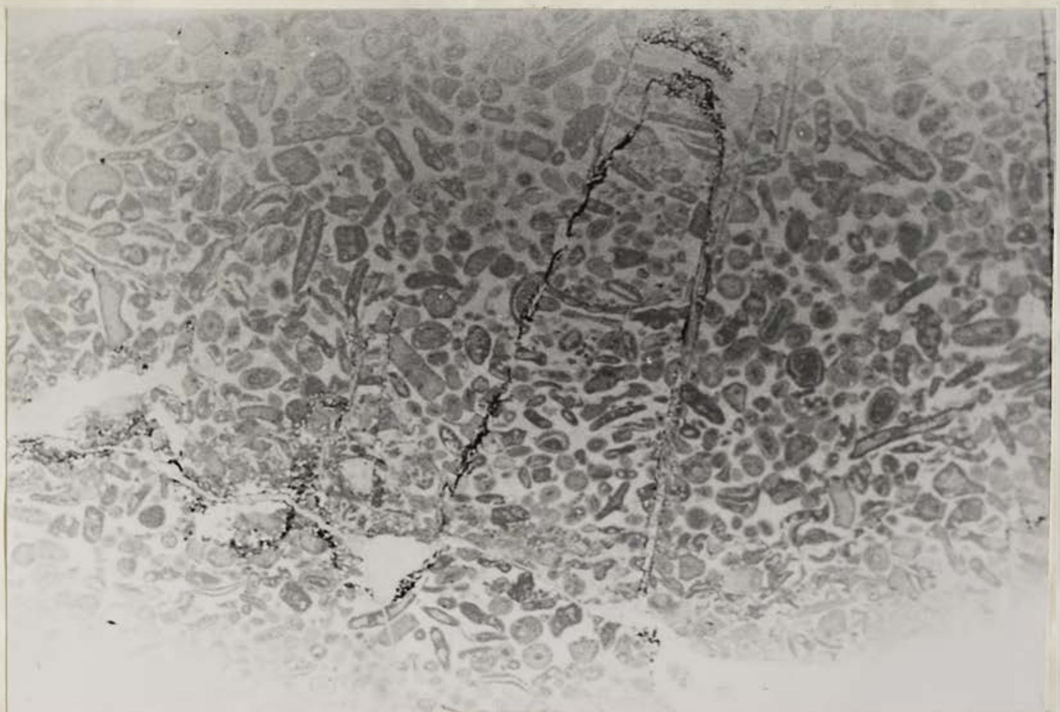


Fig. 83. Sample S-5-1. Enlarged direct photograph of the thin section. Base of the photograph is about 2.5 cm. The relationship between the stylolite seam and the oolites is well displayed.

Fig. 84. Sample S-5-1. Oolitic limestone, upper Fredonia limestone. + nicols, base of photograph = 2 mm. Accumulation of quartz grains along the inner side of a stylolitic crest. Note that oolites below the quartz grains are dissolved.

Fig. 85. Sample S-5-1. Oolitic limestone, upper Fredonia limestone. + nicols, base of photograph = 2 mm. Fluorite veinlet (black) cuts fossils and the stylolitic seam. The black triangle is a hole. Note that quartz grains are accumulated at the upper right side.

Sample no.: S-6-1 Location: Hill mine

Stratigraphic horizon: upper Fredonia

Megascopic observation: Whitish grey oolitic limestone. Stylolite is of type 5-2. Figure 86 is an enlarged direct one-to-one photograph of the thin section.

Microscopic observation (stylolite section):

Rock below stylolite: Oolitic fossiliferous limestone; quartz crystals are scattered through this rock.

Stylolitic seam:

Dark seam material: A second small stylolitic seam with low amplitude is developed only a little distance below the big main seam. The two seams are touching each other occasionally. There is more dark seam material along the upper portion of the seam; below it, abundant quartz grains are dispersed in the seam material. The upper seam has a sharp boundary with the host rock and the boundary with the lower host rock is gradual. Part of the seam material with the same composition as in the other sections is cryptocrystalline, submicroscopic and contains fibrous silica (?).

Calcite: A number of pressure-twinned calcite grains occur along the seam, practically always in vertical stretches and whenever the seam shows a reversed (enveloping) trend.

Quartz: Along the seam, many quartz grains occur and may have been accumulated (Figure 87). The quartz grains contain inclusions.

Fluorite: Is rarely seen along the seam.

Calcite veinlet: A small calcite veinlet has been displaced by both seams (Figure 88); the displacement is proportional to the thickness of the seam. In addition, the lower seam has apparently formed after the calcite veinlet and so-to-say doubled up this veinlet.

Host rock: The components (oolites, fossils, etc.) of both rocks are cut by the stylolite seams.

Fig. 86. Sample S-6-1. Enlarged direct one-to-one photograph of the thin section. Base line of photograph is about 2.5 cm. Figures 87 and 88 are microscopic details, both from the central portion of the stylolite. Note the calcite veinlet offset by both stylolite seams.

Fig. 87. Sample S-6-1. Colitic fossiliferous limestone, upper Fredonia limestone. = nicols, base of photograph 2.4 mm. Up-peak of stylolite. Orientation of quartz crystals parallel to the layers of dark submicroscopic seam material.

Fig. 88. Sample S-6-1. Oolitic fossiliferous limestone, upper Fredonia limestone. = nicols, base of photograph = 1.6 mm. Displacement of vertical calcite veinlet by a stylolite.

Sample no.: S-6-2 Location: Hill mine

Stratigraphic horizon: upper Fredonia

Megascopic observation: Fossiliferous oolitic limestone. Stylolite is of type 3-4. Figure 89 is an enlarged direct one-to-one photograph of the thin section.

Microscopic observation (stylolite section):

Rock below the seam: Well packed fossiliferous oolitic limestone with brown calcite and clear calcite as cementing media. Also it is rarely cemented with microcrystalline quartz. Euhedral quartz crystals (av. length = less than 1 mm.) occur almost only inside the brown calcite. Dark brown bituminous (?) material is scattered through some portions of this rock.

Rock above seam: Fossiliferous oolitic limestone. Clear secondary calcite cements the oolites. Microcrystalline quartz as cementing mass occurs rarely. Euhedral to subhedral quartz crystals occur mostly inside the oolites and fossiliferous spines which consist of brown calcite. This quartz shows a most peculiar rectangular orientation. Secondary calcite bands show wavy foliations and striations without any accumulationsof dark material. The directions of the striations are variable but mostly horizontal. These are probably a result of pressures arising from compaction. Clear calcite occurs as a cement around these striated areas. A large clear calcite grain has a stylolitic boundary against a layered calcite aggregate within a large downward stylolite finger.

Stylolitic seam:

Seam material: Generally much more seam material occurs at the crests or valleys. It probably consists of bituminous material which is scattered over the host rock. Also in part there is submicroscopic cryptocrystalline quartz inside the dark seam material.

Quartz: Occurs along the seam. Many more grains occur within thick seams.

Calcite: "Secondary" coarse crystalline calcite occurs only at the upper inner side of the stylolitic valleys (Figure 90). Some carbonate enclosed in the seam shows mosaic texture (Figure 90) and may have recrystallized during stylolite formation.

Fluorite: May occur scattered through some portions of this rock, but could not be recognized with certainty.

Fig. 89. Sample no. S-6-2. An enlarged direct one-to-one photograph of the thin section. Base of the picture is about 2.5 cm. The following microphotograph shows a stylolitic valley to the right of this Figure.

Fig. 90. Sample no. S-6-2. Fossiliferous oolitic limestone, upper Fredonia limestone. = nicols, base of photograph is 1.2 mm. "Secondary" coarse crystalline calcite at the inner side of the stylolitic valley. Four pieces of oolitic brown calcite are left over in the monocrystalline calcite. Note that the lower portion of the seam has a sharp boundary with the host rock (it cuts an oolite). Note also the mosaic texture of carbonates to the upper left of the picture. Three quartz crystals occur in the brown calcite which forms a dark area to the left of the picture.

Sample no.: S-7-A Location: Oxford mine

Stratigraphic horizon: Renault formation

Megascopic observation: Brownish "lithographic limestone". Stylolite is of type 2.

Microscopic observation (stylolite section):

Rock below and above stylolite: "Lithographic" carbonate (probably dolomite ?) with neat mosaic texture. This rock may have recrystallized, because under plain light the original outlines of round oolites are seen throughout the section. Fluorite occurs in traces in between calcite crystals but only in the ground mass between the oolitic features. Dark bituminous (?) seams occur interstitial between the calcite crystals. A few features are inherited from the original oolitic nature of this rock: 1) The calcite grains between the oolites are clear and larger; 2) The calcite within the oolites contains a lot of small black or brownish inclusions, which may contain the hydrocarbons collected during recrystallization; 3) fluorite and "coarse hydrocarbon" spots and perhaps occasional sulfide grains also occur between the oolites only and represent a later generation of diagenetic crystallization as discussed in connection with Sample no. 131.

Stylolitic seam:

Dark seam material: Almost a solid band of dark bituminous (?) material which contains a few grains of carbonate and quartz as well as a number of small black idiomorphic grains of sulfide (?).

Quartz: Rarely occurs inside the seam material.

Figure 91 pictures the dark seam with a "river" cut into it during grinding. This "river" is filled with the grinding debris.

Fig. 91. Sample S-7-A. Brownish "lithographic" carbonate rock, Renault formation. Nicols crossed about 45 degrees, base of photograph = 2.5 mm. Grinding hole follows the stylolitic seam (black).

Sample no.: S-7-B Location: Oxford mine

Stratigraphic horizon: Renault formation

Megascopic observation: Brownish carbonate. Stylolite is of type 2.

Microscopic observation (stylolite section):

Rock above and below stylolite: "Lithographic" carbonate rock (see description on S-7-A). Traces of fluorite and some galena in localized patches occur in between the carbonate grains.

Stylolite seam: Looks much like a meandering stream with "flow bands". Bands or lenses of fine grained carbonate alternate with the dark seam material and variable amounts of submicroscopic silica (?); a few quartz grains are also enclosed in these bands.

Fluorite: Occurs perhaps in traces in the seam. The black grains occurring in the seam appear to be pyrite or other yellow sulfide. The number of these opaque grains is quite large and the grain size varies. In one place it reaches the thickness of the whole stylolite seam. Apparently at least some of the opaque grains formed before the bending and warping of the stylolite. This is evident from their mechanical behavior.

Sample no.: S-7-C Location: Oxford mine

Stratigraphic horizon: Renault formation

Megascopic observation: Brownish carbonate rock. Stylolite is of type 2. Figure 92 is an enlarged one-to-one photograph of the thin section.

Microscopic observation (stylolite section):

Rock below and above stylolite: "Lithographic" carbonate rock with outlines of oolites. Euhedral galena occurs in between the oolitic outlines without cross-cutting the spherical oolitic outlines. Also fluorite (?) and microcrystalline quartz fillin some spaces between carbonate crystals. In one place galena (many triangular pits) has been disrupted by the compaction (vertical fractures filled out by late carbonate). The rock carbonate is always the idiomorphic constituent, suggesting therefore that at least the bulk of the rock carbonates crystallized before the galena. (The triangular pits show up on inclined illumination from the top.)

Stylolitic seam: Dark seam material shows good "streamlined" orientation. Submicroscopic quartz occurs rarely along the seam. A stylolitic disconnected sag penetrating downwards with increasing width is seen (Figure 93). An allotriomorphic aggregate of galena grains with carbonate inclusions is enclosed inside the dark band.

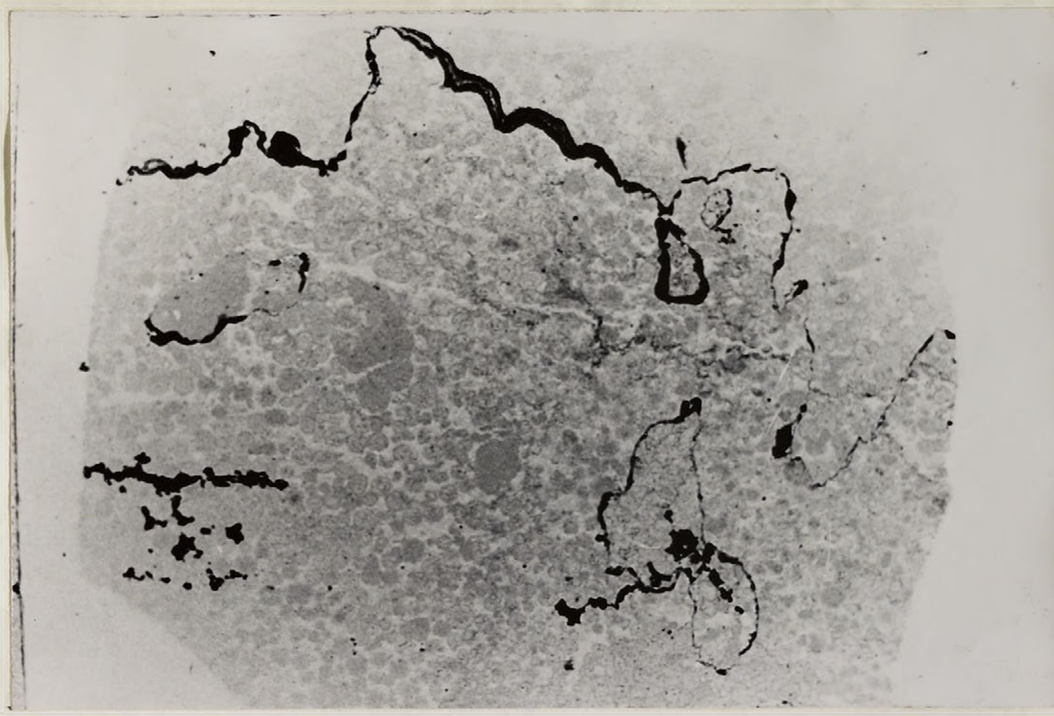


Fig. 92. Sample no. S-7-G. Base of photograph is about 2.5 mm. Enlarged direct one-to-one photograph of the thin section. Grey spheres are oolitic "ghost" outlines. Black patches to the lower left and right are xenomorphic galena crystals. The islands of rock surrounded by dark rims below the seam are portions of stylolite seams. An enlarged microphotograph of the almost isolated sag penetrating downward is pictured in Figure 93.

Fig. 93. Sample S-7-C. Brownish carbonate, Renault formation. + nicols, base of photograph = 1.5 mm. Stylolitic sag penetrating downwards into the host rock with mosaic texture. White spots in the seam are carbonate. Location in Figure 92: Upper right half.

Sample no.: 131 Location: Deardorff mine

Stratigraphic horizon: lower Fredonia

Megascopic observation: Brownish grey oolitic limestone. Stylolites are of type 1 to 2 with low amplitudes. Figure 94 is an enlarged direct one-to-one photograph of the thin section.

Microscopic observation (stylolite section):

Rock below stylolite: Oolitic limestone; oolites are packed moderately close only and cemented with clear calcite. Some of the oolites look corroded by the clear cementing calcite and also are occasionally broken at the oolitic outer rim (Figure 95). These phenomena of "corrosion" and "dislocation" of oolitic rims in the lower Fredonia oolitic limestone are discussed by LAMAR and GRAF (1957). Small pressure-solutions (stylolitic) marked with dark material demarcate the oolitic grains and frequently "chalcedonic quartz" is seen within the seam. Euhedral-subhedral quartz crystals occur only inside the oolites. A spherulite of submicroscopic quartz is seen inside an oolite.

Rock above stylolite: Oolitic limestone; oolites are well packed compared to the lower host rock and some of them are "overlapping" each other. The oolites are cemented with clear calcite and sometimes with microcrystalline quartz. Euhedral quartz grains occur almost anywhere within the brown calcite rims of the oolites. The submicroscopic quartz occurs only inside the relatively clear calcite cores of the oolites; it does not occur inside the brown calcite rims.

Stylolitic seam:

Dark seam material: The stylolite seam is composed of several smaller wavy seams (Figure 94).

Quartz: A few euhedral quartz crystals are enclosed in the seam. About 40% of the space in between the small wavy brownish seam lines consists of submicroscopic (or chalcedonic) quartz grains. Most of the submicroscopic quartz occurs inside the crystalline calcite or in between the calcite grains, and contains small euhedral crystals of carbonate. Some large grains of crystalline calcite enclosed in the stylolitic crest show pressure-twins or striations.

Sphalerite: Two grains of sphalerite occur within the seam.

Host rock: Oolites in the lower and upper host rock are cut by the seams.

Fluorite: Does not occur here.

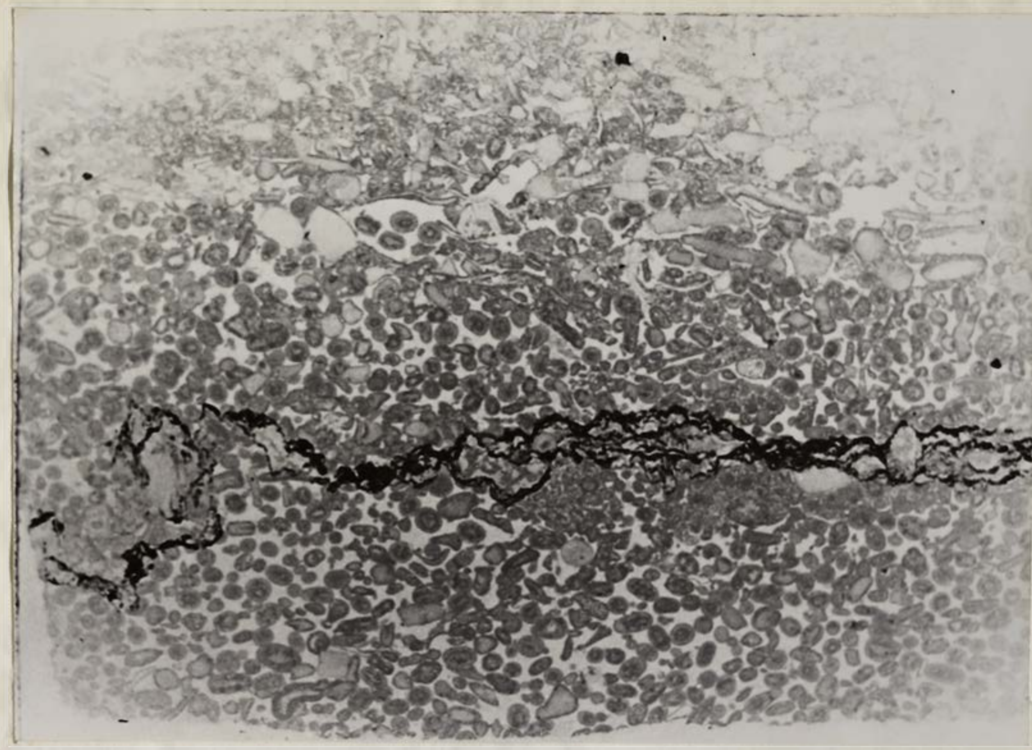


Fig. 94. Sample 131. Oolitic limestone, lower Fredonia limestone. The base of photograph measures about 2.5 cm. Note the difference in packing below and above the seam.

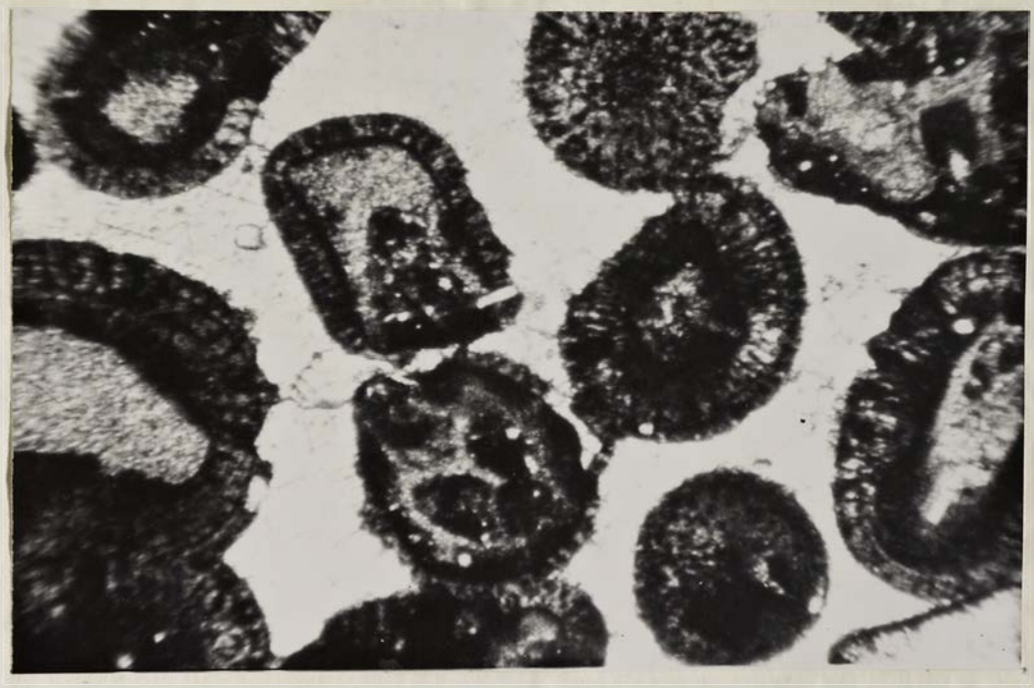


Fig. 95. Sample 131. Oolitic limestone, lower Fredonia limestone. = nicols, base of the photograph = 1.2 mm. Note the "corrosion" and displacement of oolitic rims. Small euhedral quartz grains are seen enclosed in the oolites, at the center and the right.

Sample no.: 133-1 and 133-2

Location: Pillar 69, Deardorff mine

Stratigraphic horizon: lower Fredonia

Megascopic observation: Stylolite between the oolitic limestone and dark carbonate rock (transition to sphalerite ore zone); the distance from the stylolite and the sphalerite zone is about 4 cm. The stylolite is of type 3 to 4.

Microscopic observation (stylolite section):

Rock below stylolite: Oolitic siliceous limestone cemented with clear calcite. Only a few oolites have clear central calcite cores and most of the oolites do not contain central cores; the oolites consist of "brown" calcite. Patches of bituminous (?) material occur in between the cementing calcite. Many oolitic outer rims are indistinct against the cementing calcite. A number of the euhedral quartz grains occur only inside the relatively brownish calcite rims of the oolites; but quartz may bridge two or three oolitic grains. The time of formation of the euhedral quartz is apparently later than that of the brownish, oolitic calcite, because of the drop-like dissemination of microcrystalline calcite in quartz. Apparently the formation of the quartz is also later than the cementing calcite although some of the quartz grains are euhedral against the cementing calcite. Some albite laths may also occur.

Rock above stylolite: Siliceous limestone; a few oolitic features are still present. The number of the euhedral quartz crystals increases upwards towards the sphalerite zone; some portions of the thin section consist of almost 50% of quartz crystals, some of which overlap each other and contain carbonate inclusions. Near the sphalerite zone, the place of coarse crystalline calcite is taken by microcrystalline calcite. The euhedral quartz, in this case, contains angular pieces of crystalline calcite.

Styloloitic seam: It consists of bituminous (?) material and not of clay.

Quartz: A considerable number of quartz crystals occur near or inside the seam (Figure 96).

Calcite: Most of the "secondary" crystalline calcite along the seam has "recrystallized" (?) into the microcrystalline carbonate.

Fluorite: Occurs as spots, but is not certain.

Sphalerite: Grains occur near the seam; they may be coated or sharply cut by the dark seam.

Host rock: The lower rock has cut the oolite, but the upper rock is not distinct.

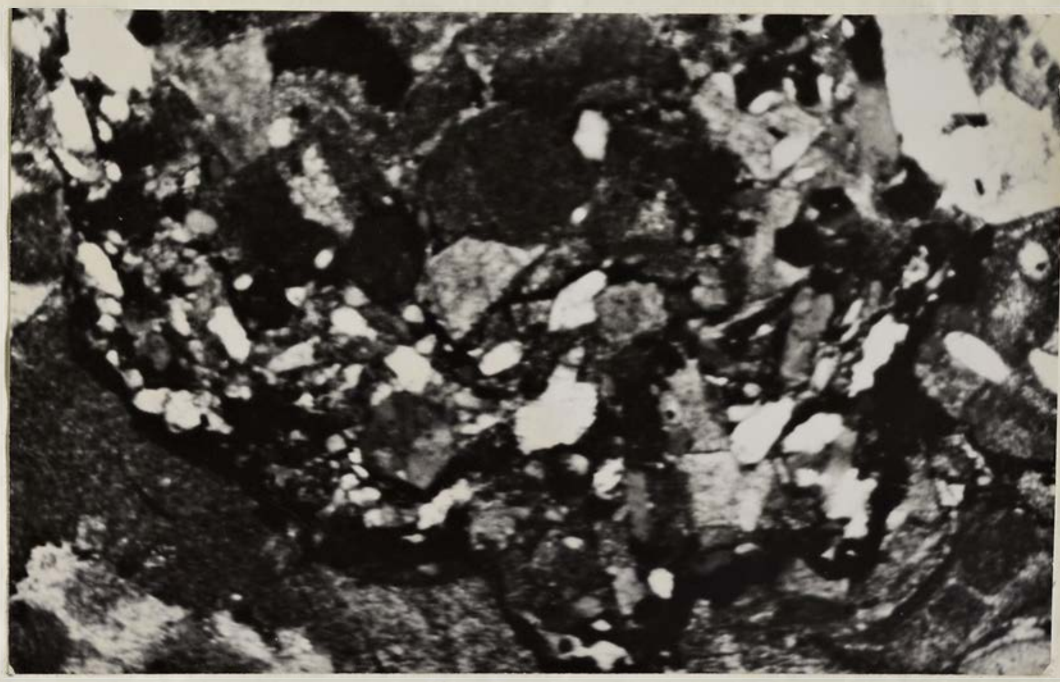


Fig. 96. Sample 133-1. Oolitic limestone, transition to banded sphalerite rock, lower Fredonia limestone. + nicols, base of photograph = 2.1 mm. Accumulation of quartz crystals at the inner side of the stylolitic valley. Stylolitic seam consists of brown bituminous (?) material, black bands below the quartz zone.

8. Summary of microscopic observations

a. Quartz:

Quartz may be classified into three groups which are (1) euhedral to anhedral, (2) submicroscopic cryptocrystalline, and (3) fibrous chalcedonic quartz.

The modes of occurrence of these three groups may be summarized as follows:

1) Euhedral quartz grains (av. length 0.1 mm) occur almost only inside the oolites; grains are much more abundant inside the dark oolitic calcite rims than inside the relatively clear calcite cores of the oolites; an exception is sample 133-1, where abundant euhedral quartz occurs scattered all over the rock.

2) Many of the quartz grains contain inclusions.

3) Some of the detrital (?) quartz grains in oolites have secondary overgrowths to euhedral form.

4) Rarely quartz serves as a cementing matrix in oolites.

5) A considerable number of quartz grains occur inside the stylolitic seam material. **Many** of them occur at the inner sides of the stylolitic crests or valleys. Their c-axes are usually parallel to the nearest walls of the stylolitic seam.

6) Submicroscopic cryptocrystalline silica (?) occurs as streaks in the stylolitic seams.

b. The "seam material"

1) Clay minerals are, according to the literature, generally believed to be the principal seam material; but in the thin section here described, most of the seam material is probably not clay.

2) The composition of the "seam material" is not known with certainty. It may consist in part of bituminous material.

3) The accumulation of this possibly organic bituminous material may have taken place as a consequence of stylolite formation.

4) The "seam material" is thick at the stylolitic crests and valleys, whereas the vertical section is very thin.

c. The different carbonates

In the host rock: Two major generations of cementing calcite are seen; first, it occurs as a thin overcoating around the oolites in the form of a "dog-tooth" type rim; secondly, as coarse grains with mosaic texture filling the remaining pore spaces. Of course, much or most of the oolite material may also consist of calcite but is normally fine grained and stained with grey or brown organic matter. According to Dr. CAROZZ (1962, personal communication)

> "The common consensus of opinion being that the brown color is due to organic matter. This, of course, has nothing to do with the different hues of gray related to the grain size of the calcite crystals or to the presence of clay minerals segregated during the processes of fibro-radiated recrystallization, undergone by the oolites during diagenesis."

In or near the stylolitic seam: (1) Coarse grained calcite frequently occurs at the inner side of the stylolitic valleys and crests. (2) Thin calcite grains along the vertical stylolitic section occasionally show pressure-twinning.

Since this type of coarse crystalline calcite, if present, occurs always near the stylolitic seam, the crystallization of this calcite may be related to stylolitization. It may be that the carbonates were precipitated during or towards the end of stylolitization.

d. Fluorite

1) Fluorite occasionally occurs in spots along the stylolite seam.

2) In many cases, fluorite contains inclusions. Because of the sizes of inclusions, their composition could not be determined. However, inclusion

of carbonates could be determined.

e. Barite

Barite does not occur inside the stylolitic seams. It's most abundant occurrence is in the rocks described as rhythmites and here it almost always shows excellent plumose patterns including euhedral fluorite.

f. The behavior of oolites

1) The shape and the cores of the oolites vary.

2) "Corrosion" and "displacements" of oolitic outer rims have been observed occasionally.

3) Distorted oolites and pseudoolites as defined by CAROZZI (1960) are not present.

4) Many cores consist of relatively clear calcite, and rarely microcrystalline or fibrous chalcedonic quartz.

5) Dark oolitic calcite often contains euhedral quartz.

6) The stylolitic contacts between the oolitic grains are seen and often sharply cut by the stylolitic seam.

g. Paragenetic sequence

Paragenetic charts can be made for each rock type. An example is given with the description on p. 166 and 167.

h. Pressure effects

i. The RIECKE principle

The principle states that a crystal in contact with another undergoes solution at points of maximum stress and precipitation at points (or areas) of least stress. As TURNER and VERHOOGEN (1960, p. 476, Igneous and Metamorphic Petrology) stated this principle may apply "if an elastic body is subjected to stresses which are non-homogenous".

During compaction of sediments, the individual grains are pressed against each other and it is generally assumed that solution takes place according to RIECKE's principle.

The mathematical expression of the principle is (von ENGELHARDT, 1960, p. 23):

$$\ln \frac{c_p + \Delta_p}{c_p} \doteq \frac{V_f \cdot \Delta_p}{RT}$$

where c_p refers to saturation concentration, Δ_p to difference in pressure, V_f to mole volume, R to gas constant, and T to the absolute temperature of the system.

In many cases the thin sections, oolitic grains, and other aggregates such as calcite, quartz exhibit effects of probable "RIECKE dissolution". They are described on Figures 73 and 79 and are mentioned on the descriptions on samples S-1-4 and 131.

ii. Pressure twinning

In many places in the thin sections calcite grains were seen to have a certain number of parallel "stripes". These were described as pressure twins because their formation can be shown to be linked almost without exception to vertical stylolite seams which show micro-fault planes. Also, the "stripes" are parallel to crystallographic planes of the carbonates.

Pressure twinning has been discussed in almost every mineralogy and some structural geology textbooks and also in texts on solid state physics; so for example by AZÁROFF (1960, p. 157 ff.) and KITTEL (1953, p. 539). A number of authors picture pressure twins in carbonates. HELMBOLD (1953) observed pressure-twins in feldspars in graywackes which apparently formed during compaction.

The following figures in this thesis picture pressure-twins: Figures 100, 101, 103, and 104. All gradations are observed, from just a few lamellae to a complete "squeezing out" (sets) of the carbonate grain.

The fact that these pressure twinned grains or areas, as also many micro-faults, are limited and strictly local, suggests that the pressure exerted also was confined to a small local area. Therefore, this area can only be visualized as set up between local "trapped" grains during compaction. If "epigenetic" (post-lithification) pressure would have produced them, one should be able to see the faults and pressure-twinned zones extend beyond the seams or local spots.

F. Genetic approaches to the stylolite problem and conclusions

1. First order criteria

The "first order criteria" consists of the individual observations and measurements. They are subdivided into geometric criteria (Gm) and compositional criteria (Gc). The following list of first order criteria is actually a short summary of geometric and compositional observations discussed in the previous sections.

Geometric criteria (Gc).

Gm 1: Six basic types of stylolites are classified into six basic patterns.

Gm 2: Stylolitic seams are essentially intergranular.

Gm 3: Stylolites are essentially parallel to the bedding planes.

Gm 4: Cross-cutting stylolites are rare. They are generally of the tapered and pointed peak type with low amplitudes and thin seam material.

Gm 5: Stylolites may merge into shale or clay partings.

Gm 6: Clay seams in baritic shale change laterally into stylolites.

Gm 7: Consecutive horizontal displacement of an inclined stylolite by a number of horizontal stylolites is observed (Figure 45).

Gm 8: Calcite veinlets are displaced along the horizontal stylolites.

Gm 9: The walls of the stylolitic columns are striated and slickensided.

Gm 10: Stylolites occur on the horizontal layers of a broken piece of dolomite and not along the vertical and bottom portion (Figure 62).

Gm 11: Stylolites trend downward into surfaces of slump structures and display wave-like patterns near or along the slump surfaces. (Figures 57, 64, 65, 68, and 70)

Gm 12: The stylolitic seams become thicker and their amplitudes decrease near the slump **surface** (Figures 64, 65, 68, and Graphs 1 and 2).

Gm 13: Host rocks above and below the stylolitic seams are rather sharply cut by the seam.

Gm 14: Seam material is thicker at the crests and valleys of stylolites than along the vertical sections.

Gm 15: Stylolitic sags penetrating downward with an increasing width were observed (Figures 92 and 93).

Gm 16: Seam material shows a linear orientation parallel to the nearest sides of the stylolitic seam, but occasionally shows convolutions within the seam.

Gm 17: The c-axes of quartz grains occurring inside the stylolitic seam are usually parallel to the nearest walls of the stylolitic seams.

Gm 18: Sub-microscopic cryptocrystalline silica streaks in the stylolitic seam show orientation parallel to the side walls of the stylolitic seams.

Gm 19: Pressure twins of calcite within vertical sections of the stylolites were frequently observed.

Gm 20: Horizontal stylolitic contacts between two oolitic grains were observed.

Gm 21: Vertical stylolite seams often sharply cut oolites.

Gm 22: Some euhedral quartz grains show wavy outlines along intergrowth boundaries with other quartz grains, plus some dark material.

Gm 23: Coarse crystalline calcite grains occasionally show stylolitic boundaries.

Gm 24: An ovoid oolite is cut by a small up-peak (?) stylolite (Figure 79).

Gm 25: "Snow-ball" orientation of an oolite was observed near the entrance into a long narrow valley of a stylolite.

Gm 26: A series of microscopic stylolitic seams may consist of one megascopic stylolite (Figures 75 and 94).

Compositional criteria (Gc):

Gc 1: The lithology of the rocks below and above the stylolitic seam may or may not be the same.

Gc 2: A considerable number of quartz grains occur inside the stylolitic seam material. Many of them occur at the inner side of the stylolitic crests or valleys. The lengths of the euhedral quartz grains in stylolite seams are almost the same as those of quartz in the host rock.

Gc 3: Most of the seam materials are also associated with streaks of submicroscopic and cryptocrystalline silica (?).

Gc 4: The composition of the dark staining material is not known. Most of the seam material is probably not clay. This composition may consist in part of bituminous material collected from the dissolved oolites or other components of the rock.

Gc 5: Coarse calcite frequently occurs at the inner side of the stylolitic valleys and crests.

Gc 6: Vertical sections of the stylolitic seams show that the sections are frequently bordered by thin calcite streaks or grains which frequently display pressure-twinning. The "striations" are often somewhat curved or inclined toward the inner side of the stylolitic columns. Generally the lengths of the striae in this calcite are longer at the inner side than on the outer side of the stylolitic column.

2. Second order criteria:

Second order criteria are the preliminary interpretations and conclusions derived from the first order criteria. These second order criteria may be based on one or more first order criteria."

1. Gm 2, Gm 9, Gm 19, and Gm 20.

   The formation of stylolites is caused by a pressure which existed between two units of rock. The direction of the stylolitic columns reveals the direction of this pressure.

2. Gm 2, Gm 20, Gm 21, and Gm 24.

   The boundaries or points where grains were touching each other, were dissolved under stress. Further continuation of the stress may have dissolved much of the aggregates, developing larger depressions. The stress necessary to dissolve aggregates is dependent upon the composition, size, crystallographic orientation, concentration of solution near the contact zone between the aggregates. According to MORAWIETZ (1958, from Prof. von ENGELHARDT, 1962, personal communication), microstylolites between limestone pebbles were produced under a few meters of overburden.

3. Gm 11.

   Downward inclination almost parallel to the slump-slopes indicates that stylolites may have been developed before the formation of the slumps; thus the stylolites in carbonate rocks may have been formed when the rock was still in a semi-soft state.

4. Gm 10 and Gm 5.

If stylolitization had been post-brecciation (after lithification), stylolites would have been developed continuing into the carbonate matrix of the carbonate rock.

5. Gm 7 and Gm 8.

Horizontal displacement appears to have taken place prior to stylolitization, because horizontal movement over a rugged surface is hard to visualize.

6. Gc 4.

The seam material normally may be the insoluble residue of stylolitization.

7. Gm 17, Gc 2 and Gc 3.

Orientation of quartz grains parallel to the seams may be due to the pressure, or to oriented growth. Some of the quartz grains may be insoluble residues. Others may have crystallized probably at the end of stylolitization. The origin of the silica is not known; however, it may have been derived from the host rock which has dissolved, or from silica-rich interstitial pore solutions.

8. Gc 2 and Gc 5.

The quartz and calcite grains at the inner side of the stylolitic seam may have crystallized during or at the end of stylolitization. The origin of the calcite may be the calcium carbonate in the host rock dissolved by solution.

9. Gm 5 and Gm 6.

A thin shale layer could alone develop into a stylolitic seam during the compaction of sediments, even without the accumulation of any insoluble residue. The development of the stylolitic patterns along the clay layer may depend on its thickness, physical state, and pressure exerted.

3. Assumptions and logic

(1) The differential pressures and dissolving agents are believed by some geologists (STOCKDALE, 1922; TWENHOFEL, 1926; BASTIN, 1933; PRICE, 1934; et al.) to be essential in the formation of stylolites according to the solution-pressure theory. Differential pressure only as a cause of stylolitization has so far been proposed in the contraction pressure theory (SHAUB, 1937). It is hard to conceive extreme values of differential pressures and dissolving agents along the bedding planes of the sediments in both lithified and unlithified rocks, to produce the valleys of stylolites. It is here proposed that there are no extreme differential sets of pressures and dissolving agents within the stylolite seam.

(2) The highest pressures exerted were at the grain contacts of the aggregates.

(3) The geometry of the stylolites is probably a function of the physical state of the sediments, the mineralogy, pressure, solution, and time of stylolite formation.

(4) The pressure which formed stylolites was caused by the overlying rock. It may not have been high.

(5) The pore solutions may have played an important role in the formation of stylolites, in particular in the deposition or redeposition of quartz and calcite.

C. Conclusion

On the basis of the evidence brought out by the first and second order criteria, one may conclude that stylolites are formed during compaction of the sediments and thus are a part of the diagenetic process. The formation is initiated between grain boundaries of loose aggregates and becomes visible by the presence of a thin clay layer or a seam of residue material.

CHAPTER VII. SULFIDES IN OOLITIC LIMESTONE

A. Introduction

Three thin-sections and one polished section made from oolitic limestone with disseminated sphalerite grains from the lower Fredonia limestone were studied in detail in order to understand the geometric and the time relationships between the sphalerite, the associated structures (stylolites) and the minerals occurring in them.

The rock studied was collected at the distance of about 220 m east of the shaft of the Deardorff mine, and at 50 cm below the basal dark argillaceous carbonate layer of the upper Fredonia limestone (50 cm below the boundary between the upper and lower Fredonia limestone).

Quite close to the sampled spot, a reverse fault with a displacement of about 25 cm (strike and dip are N. 50° E., 85° N. W.) is filled with calcite, quartz and bituminous material which yields a distinct petroleum odor.

Figures 97, 98, and 99 are the enlarged direct one-to-one photographs of the thin sections studied. The black spots or rims in the oolites are mainly sphalerite grains; small portions of black material occur in the matrix and are also described in detail; the white interstitial ground mass consists of cementing calcite. As will be described on the next pages and illustrated with microphotographs, the sphalerite occurs almost always in the oolites as shown on Figures 97, 98, and 99.

In addition to the three sections mentioned above, two thin-sections made from oolitic limestone from the lower Fredonia limestone in the Hill mine were studied. Figures 116 and 117 show these sections.

Fig. 97. An enlarged direct one-to-one photograph of thin section no. 118a. Black spots or rims are sphalerite. To the right, a calcite veinlet cuts the host rock. The base of photograph measures 2.3 cm.

Fig. 98. An enlarged direct one-to-one photograph of thin section no. 188b. The base of photograph measures 2.3 cm.

Fig. 99. An enlarged direct one-to-one photograph of the thin section no. 118c. Note the stylolitic "streak" rich in sphalerite. The base of photograph measures 2 cm.

Fig. 100. Plain light, base of photograph about 2.2 mm.

Fig. 101. Plain light, base of photograph about 2.2 mm. Right side of Figure 100.

Fig. 102. Plain light, base of photograph about 2.2 mm. Left side of Figure 100.

B. Description

Text to Figures 100, 101, and 102:

These three Figures, 100, 101, and 102, show an area with details of genetic interest. They are enlargements from Figure 99. They are photographs of an interstitial space with pressure twin calcite. One large sphalerite grain enlarged in Figure 103 (sphalerite is always black) shows a clear rim of calcite, the same as seen on galena in Figure 117 (sample S-1-1). Beyond this rim of calcite extends a large interstitial field of pressure-twinned polysynthetic calcite which on the other side is limited by a stylolite seam with black rims. Note that the pressure-twins are in part optical continuations of the calcite rim around the sphalerite grain and therefore apparently later. The clear calcite rim obviously has undergone the same pressure-twinning as the field of interstitial calcite. Note also that the pressure-twins are slightly bent (Figures 100 and 101). In the upper right corner of Figure 102 they radiate around a sphalerite grain which apparently served as a center of pressure concentration. In some portions of this radiating scheme a section of the radiating field appears to have been recrystallized. In the center of the larger pressure-twinned calcite field (Figures 100 and 101) there are also two patches of calcite which are not optically continuous with the twins and apparently also recrystallized. The left side of Figure 100 and the center of Figure 192 apparently suffered some fracturing although not very much. Some of the grains of sphalerite are also surrounded by clear rims of calcite; this calcite outside, inside, and between the sphalerite fragments is optically continuous with the calcite of the matrix.

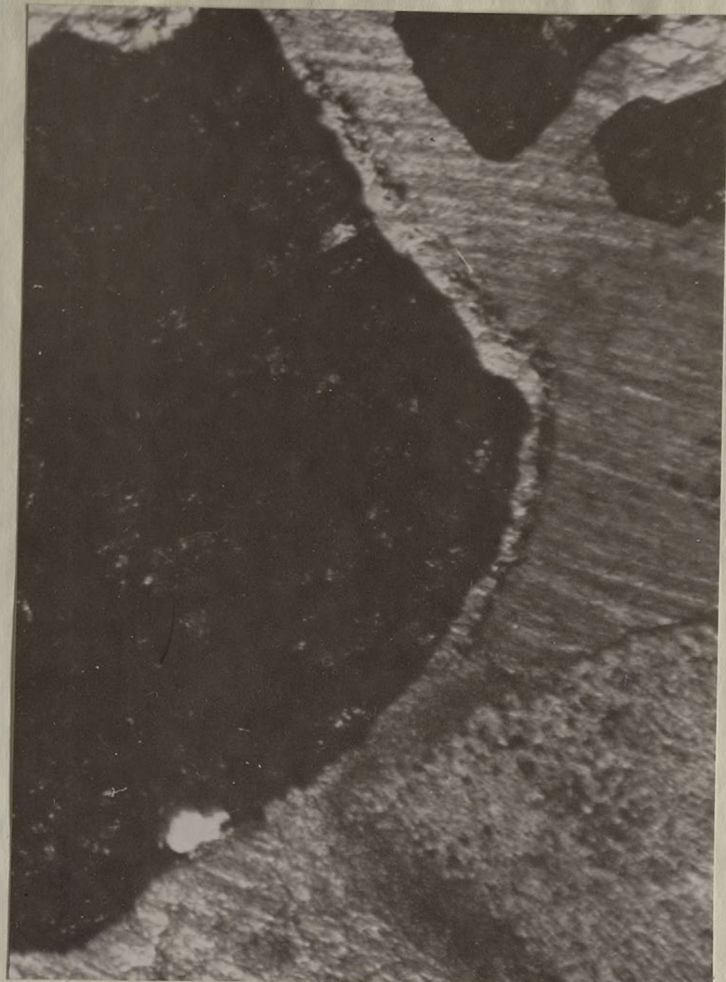


Fig. 103. Plain light, base of photograph about 0.7 mm.

An enlarged photograph of the portion of Figure 100 where a calcite rim around a sphalerite grain occurs. On the left the calcite rim almost disappears at the junction where dark calcite of an oolite just touches the sphalerite grain boundary. The "striation" of the pressure-twinned matrix calcite (to the right) is also clearly seen and so is the fact that the calcite rim is largely optically continuous with the calcite lamellae of the matrix.

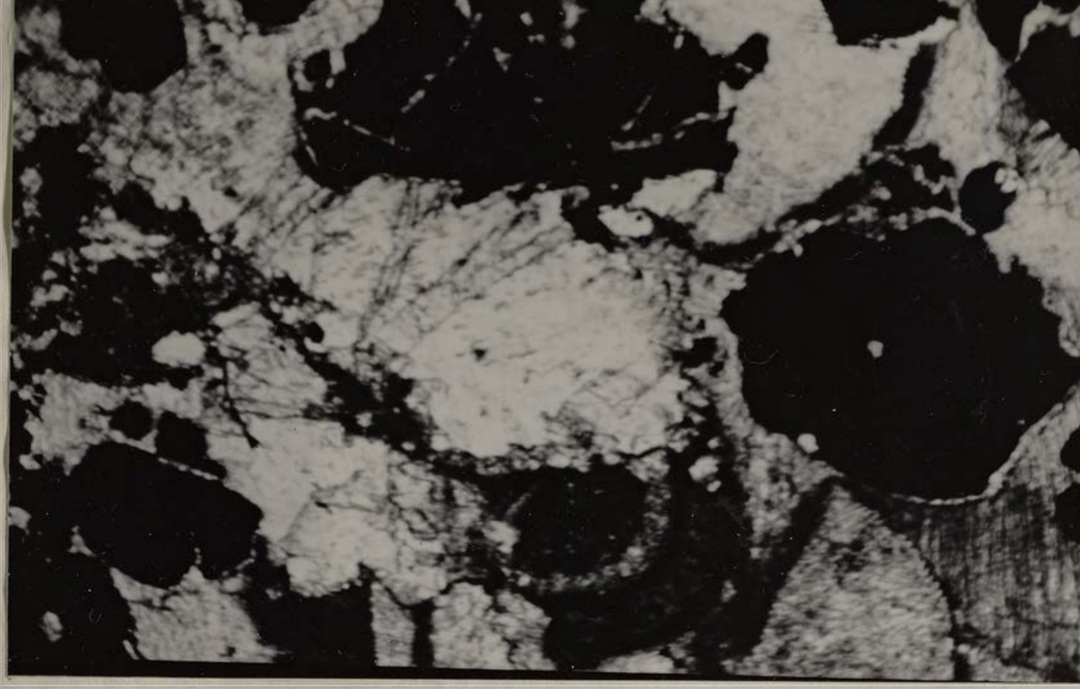


Fig. 104. Plain light, base of photograph about 2.2 mm.

Calcite veinlets, adjacent to the area of figures 100, 101, and 102, cut across an area of undulating quartz (?). These veinlets are perpendicular to a portion of the stylolite seam pictured in Figure 101. The sphalerite grain (very dark grey) again is surrounded and traversed by a clear calcite rim. The quartz area under stress apparently broke and the calcite recrystallizing from Reicke-dissolution of oolites or from remaining pore spaces filled the fractures in the quartz and the adjacent sphalerite, to form the veinlets. At the bottom, a partly eliminated oolite is cut by a stylolitic seam. The main area between the sphalerite and this stylolite seam is quartz with highly undulating patchy extinction.

Fig. 105. Plain light, base of the photograph about 2.2 mm.

Oolites with partial replacements of the dark portions by sphalerite. One large oval oolite with a V-shaped inside space containing monocrystalline calcite shows replacement of the outer shell in two portions. To the lower left of this is a small perfectly round oolite which is completely replaced. In the clear calcite matrix there are traces of a black material at grain boundaries (in places these show angular outlines). To the lower right an irregular shaped oolite also contains some sphalerite in its rim and again the small inside with clear calcite is not touched by the sphalerite but rather perfectly framed by it.

Fig. 106. Crossed nicols, base of photograph about 2.2 mm.

To the lower left is an oolite almost completely filled with sphalerite. Note the idiomorphic boundaries of sphalerite particularly toward the inside of the oolite where dark carbonate remains. In the center there is an almost perfectly round oolite with idiomorphic quartz crystals dispersed through it; one quartz grain in the right side grows across the round oolite's boundary into the adjacent oolite. This adjacent oolite (to the right) has two centers: the larger and the brighter center contains radial and perhaps chalcedonic quartz in what might be called an "hourglass" structure. In the other center there are two more or less idiomorphic grains of sphalerite.

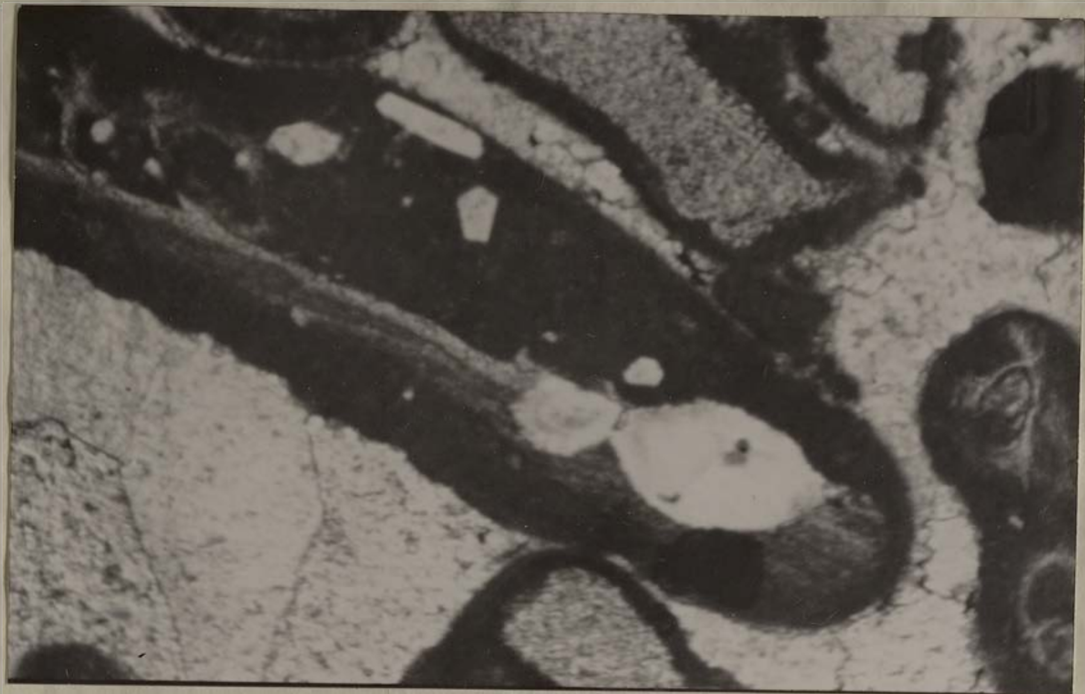


Fig. 107a. Plain light, base of photograph about 2.2 mm.

Fig. 107b. Crossed nicols, base of photograph about 2.2 mm.

Text to Figures 107a and 107b:

This is a long, irregularly oval oolite displaying two types of quartz. In the lower end there are two egg-shaped areas of concentrically textured masses of chalcedonic quartz. Below the larger mass a grain of sphalerite sits in the dark oolite mass. In the central portion of the oolite, close to the upper rim are located three larger grains of quartz and a few small ones. They are all more or less idiomorphic. Two of the larger ones appear to be cut more or less vertically to the c-axis whereas one of them is cut parallel to the prism. In the matrix of the oolites close to this large quartz grain traces of a black material are seen between the boundaries of matrix of a calcite grain.

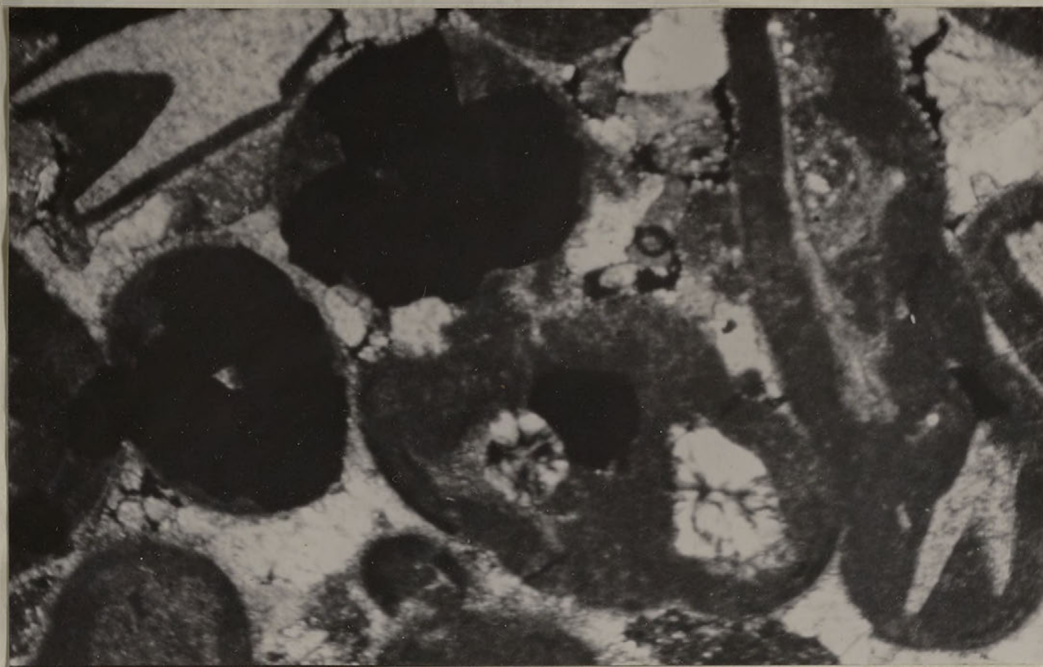


Fig. 108. **Plain light,** base of photograph about 2.2 mm.

In the center, lower half, an oolite contains two areas with chalcedonic quartz in its two centers. Adjacent to the left center there is an idiomorphic sphalerite grain, allotriomorphic only against the chalcedonic spherule. It may be considered to be later than this spherule, and obviously did not replace it. This oolite contains in the lower rim a brownish banding which is fairly common in this rock. Toward the upper and lower left two oolites are almost completely filled with more or less idiomorphic sphalerite grains. Apparently sphalerite could crystallize almost uninhibited within the dark oolite material. Toward the right side, an elongated oolite contains some small crystals of more or less idiomorphic quartz in its upper center. The matrix again consists of a mosaic of clear calcite with dark material along the grain boundaries.

Fig. 109. Plain light, base of photograph about 2.2 mm.

Three oolites with dark rims or zones which may be sphalerite, manganese oxide, iron oxide or bituminous material. The dark grains within the oolites are sphalerite, the black irregular intergranular masses of the matrix is an unknown black material. Toward the upper right a large idiomorphic quartz grain bridges two oolites. A small quartz grain occurs in the "double bar" oolite to the lower right.

Fig. 110. Crossed nicols, base of photograph about 2.2 mm.

Two oolites with dark material (bands) in their rim. To the lower right sphalerite replaced a rim and transgresses from this into the matrix and the clear rim. This is because this oolite occurs within the streak of abundant sphalerite.

Fig. 111. **Plain light**, base of photograph about 2.2 mm.

Figure 111 shows a portion of irregular streaks of sphalerite traversing in a wavy pattern the oolitic limestone. Note that in this case sphalerite does not play the same role as so far described. Here, it occasionally forms independent grains within clear cement or central oolitic calcite. In this streak of abundant sphalerite, the unknown black material and occasionally stylolitic irregular lines truncate oolites. It is perhaps significant that sphalerite leaves the rule of its geometric occurrence which is established in the rest of the rock, only in this "streak" rich in sphalerite and with stylolitic seams. Perhaps the accumulation of sphalerite took place by means of stylolite formation, i.e., by the Riecke-type of corrosion of oolites and matrix. The sphalerite and black material in fact look like an accumulation of an "insoluble residue", because their shape is essentially that of the grains in the major rock mass.

Fig. 112. Plain light, base of photograph about 2.2 mm.

Oolite almost completely filled with sphalerite and containing idiomorphic quartz crystals. The quartz is not replaced. In an adjacent bean-shaped oolite, there is also an elongated quartz crystal. Quartz within oolites was also pictured in Figures 106, 107a, b, and 109.

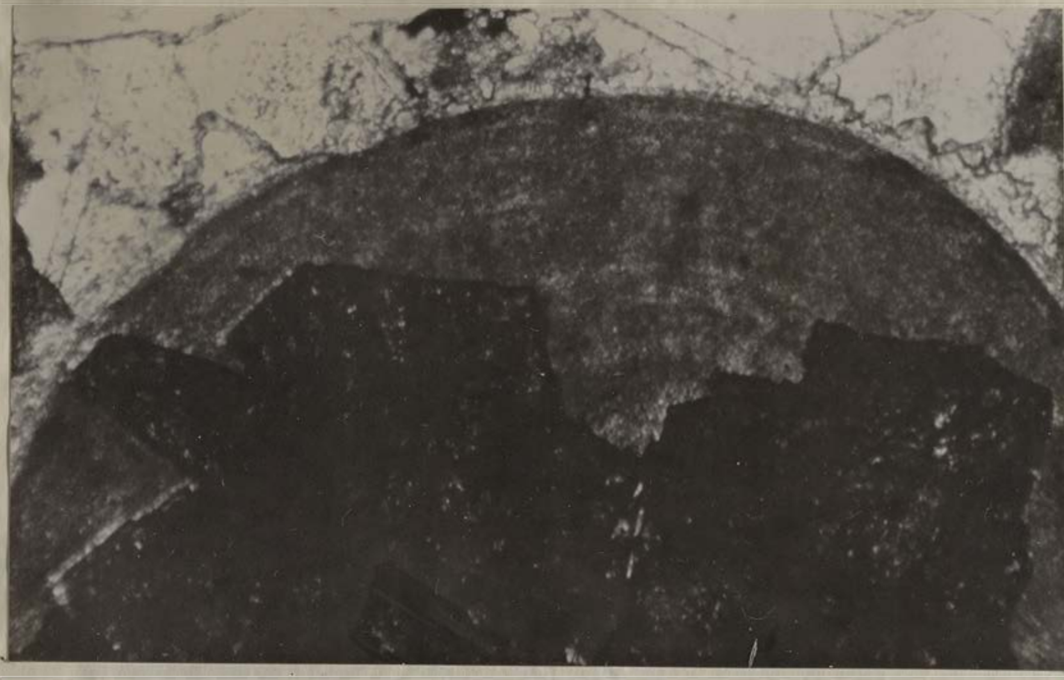


Fig. 113. Plain light, base of photograph about 0.7 mm.

Sphalerite grains are seen inside spherical oolite, showing euhedral forms (at the center line of photograph) within the oolite. To the upper left outside of the field of this photograph, the grain boundary of the sphalerite coincides with the outer oolitic rim. Note thin layers of clear calcite within the oolite at the surface of the sphalerite crystals on the upper left and the left center of the photograph. Apparently the euhedral sphalerite cuts the fine layers of dark oolitic calcite. There are apparently two different generations of cementing calcite; one which occurs as a "dog-tooth" type rim around the oolites but of irregular thickness, the other as more coarse crystalline calcite, "filling" the triangular spaces between the oolites. The latter often occurs as a mosaic of two to ten grains of calcite.

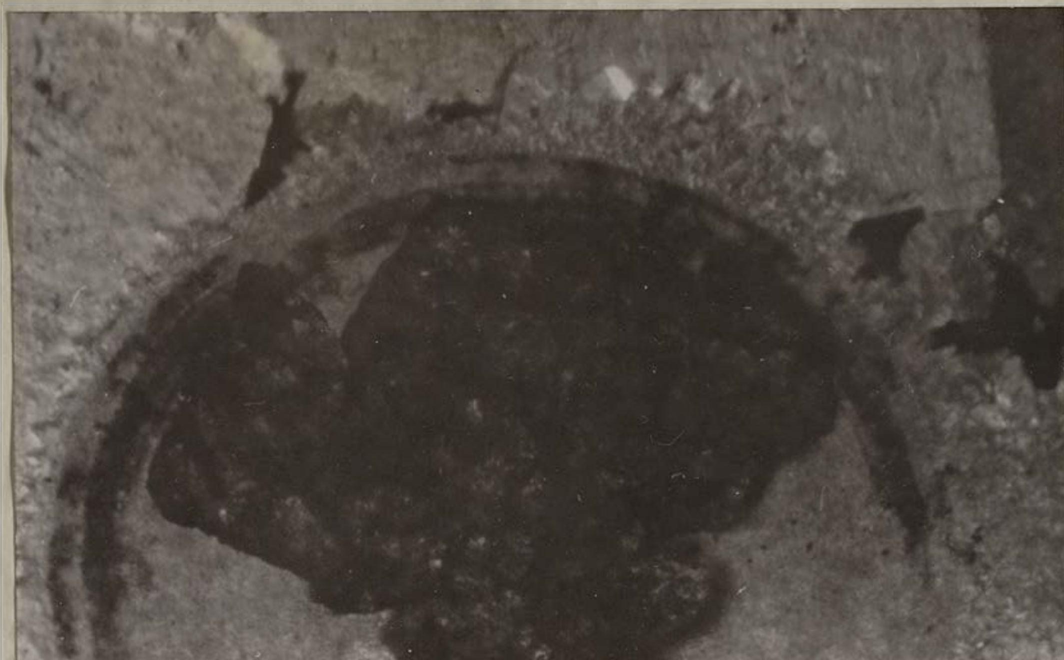


Fig. 114. **Plain light,** base of photograph about 0.7 mm.

Idiomorphic sphalerite crystals within an almost perfectly spherical oolite with dark zones along the outer rim. The sphalerite is located within the dark zones except in three isolated spots, where three crystals penetrate the dark zones. The unknown black material to the upper right and to the left almost always occurs between the thin layers of cementing calcite covering the oolites, and the coarse crystalline calcite of the cement, which suggests that the formation of the black material was probably followed by the crystallization of the thin over-coating of calcite.

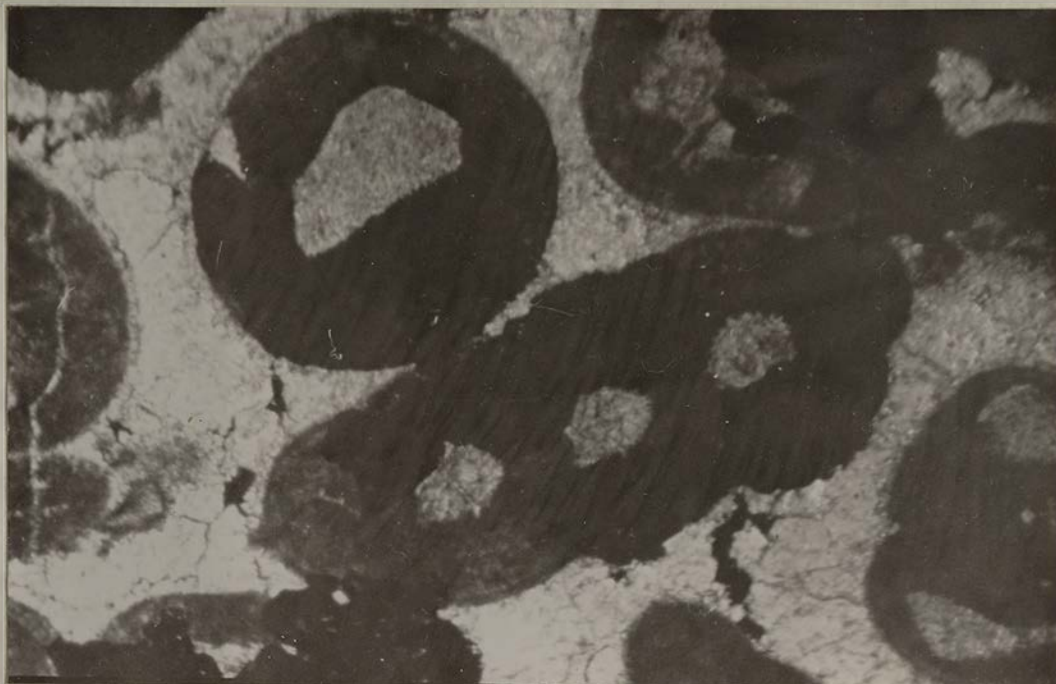


Fig. 115. Plain light, base of photograph about 2.2 mm.

Donut-shaped sphalerite, at the upper left did not replace the relatively clear calcite core of the oolite. It fills almost the whole mass of the dark oolite rim. In the center an oolite with three clear calcite cores shows partial replacement of the dark rim by sphalerite. To the lower center, sphalerite bridges two adjacent oolitic rims. Bituminous material is seen in between the cementing calcite crystals.

Fig. 116. Sample S-1-1. Oolitic limestone, lower Fredonia limestone. Crossed nicols, base of photograph :: 1 mm. Three types of calcite occur, (1) light grey inside of oolites, (2) dark grey rims, and (3) interstitial calcite. Galena appears to replace primarily type (2) and then type (3) calcite, leaving type (1) intact.

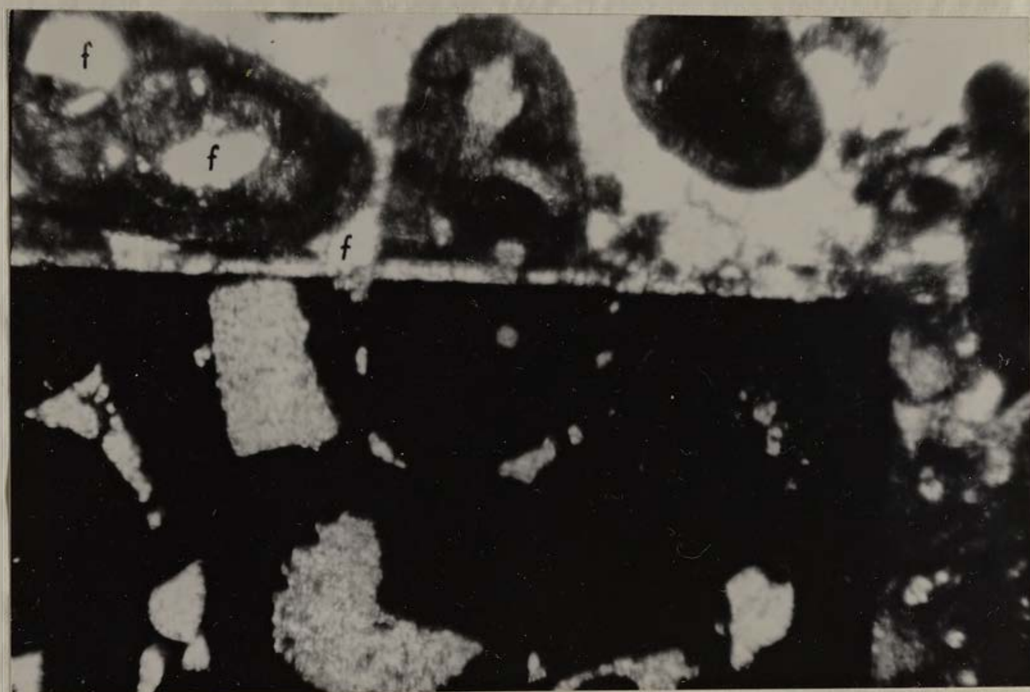


Fig. 117. Sample S-1-2. Oolitic limestone, lower Fredonia limestone. Plain light. The base line of photograph measures 2.2 mm. As in sample S-1-1, Figure 116, there are the same three types of carbonates; and only type 2 and 3 appear to be replaced by galena. An additional feature in this case is the thin layer of clear calcite over one side of the galena cube. Three spots with fluorite (f) are also seen.

C. Conclusion

(1) There are two different generations of cementing calcite; one which occurs as a "dog-tooth" type, forming a thin rim around the oolites, the second as coarse crystalline calcite "filling" the remaining spaces between the oolites.

(2) Authigenic euhedral quartz grains occur almost only inside the dark oolitic calcite.

(3) The chalcedonic quartz spherules were formed before the formation of sphalerite.

(4) Sphalerite formed only within the dark oolitic calcite rims which probably consist of calcite with organic matter. Sphalerite probably started to form in the oolite from the outer dark rims toward the inner sides of the oolites. It must have formed before the precipitation of the "dog-tooth" calcite rim.

(5) Sphalerite did not replace relatively clear calcite and quartz or chalcedonic quartz.

(6) The thin calcite rims around some of the sphalerite grains formed before the formation of pressure-twinning, because it may have undergone slight pressure-twinning, as shown in Figure100 and shows crystallographic continuity (same extinction angle). This rim around sphalerite may occupy the same paragenetic place as the rims around the oolites.

(7) The stylolitic streak rich in sphalerite may be the result of "stylolitic" dissolution of oolites and cementing calcite. The sphalerite grains which are probably readily insoluble were accumulated along the zone where solution has occurred.

(8) Polysynthetic calcite inside a stylolitic crest appears to have been formed by pressure-twinning.

(9) An area of chalcedonic "quartz" has been fractured probably due to the stress. This quartz shows undulating extinction and its fractures are filled by calcite. This intruding calcite may have been derived from "Ricke-dissolution" of the oolites and/or of cementing calcite.

(10) Galena appears to have replaced first the dark oolitic rims and then also the cementing calcite or it may just have filled the spaces between the oolites, before or with the clear cementing calcite. The clear calcite cores of oolites were not replaced by galena. Since galena left untouched the clear calcite in the core of oolites, one may justify the assumption that it did not replace the even clearer matrix calcite, but rather formed before it.

APPENDIX I

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39. Change of texture during the process of consolidation. Consolidation forms not only the inner texture of a rock considerably, but is reflected also in the exterior properties of a rock, in so far as it (the texture) produces sometimes a marked change in the shape of the bedding plane (formation of the stylolites and of cone-in-cone textures) and changes the rock color, as well as the deformation of spherolites, concretions, geodes, and septaries.

Stylolites: The stylolites represent a zig-zagging (intended) connection between the broader planes of two beds or layers and of one and the same layer. Such a plane is characterized by a columnar protrusion on the bedding-plane, which consist of the same material as the overlaying rock.

Oftentimes one observes along the coating surface especially in its indentation, remnants of clay, vertical striations and furrows, which appear to have been formed, as if tooth-like protrusions would have been pressed in the underlaying bed.

Cases have been described in which stylolites cut through oolites and some of the oolites are pushed into the styloltic columns. The change of the stylolite surface amounts to 2 cm in average but there are also stylolites known (microstylolites) which are considerably well developed, in which the height of the protrusions upwards and downwards measure at the most a few mm. And even only tenths of mm. For all types of stylolites the dented profile is very characteristic.

The stylolites are not always restricted to bedding planes. Often they are found also within a bed, where they form sometimes a complicated system of planes which transect each other.

Stylolites are most abundant in limestones and dolomites, but they are also found in salt rocks.

The formation of stylolite is undoubtedly connected with selected solution under pressure which occurs in certain parts of the beds in contact, and which leads to a certain reduction of their thickness which is also typical for their epigenesis.

Less provable is a formation of stylolites in plastic rocks before its hardening. Very uneven corroded bedding plane which reminds one of stylolites is classified by G. I. TEODOROVITCH under the designation suture-stylolitic (pressure-suture -- German translator). According to the opinion of this investigator it forms by solution of a semi-hardened shallow water calcareous precipitate, if it was brought out of the water for a short time and was transformed subsequently. Therefore, G. I. TEODOROVITCH assumes that stylolites of calcareous rocks have a definite paleo-geographic significance in so far as they are connected with shallow water zones which dry out periodically.

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